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Feasibility of PCM Slurry for Improved Thermal Efficiency of an Historic Public Building in Ireland.

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FEASIBILITY OF PCM SLURRY FOR IMPROVED THERMAL EFFICIENCY OF AN HISTORIC PUBLIC BUILDING IN IRELAND.

A Thesis

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of

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To my parents – for always squeezing through the ‘bottleneck’ with me.

To Jake – for all his belief in me.

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ABSTRACT

Doyle, Áine M. M.S., Purdue University, December 2015. Feasibility of PCM Slurry for Improved Thermal Efficiency of an Historic Public Building in Ireland.

Using a case study approach, this body of research investigated the issue of energy use and thermal comfort in historic buildings. The purpose of this research was to evaluate if the addition of the latent heat storage material microencapsulated phase change material slurry to the central heating system of a historic building could reduce energy consumption and increase the thermal comfort of the occupants. The investigation centered around a field experiment exploring the influence of different heating systems on a test room, the results were then inferred to a protected public building. The results showed a slowdown in the rate of cooling during the testing of the subject material and a reduction in the number of heating cycles required.

CHAPTER 1 INTRODUCTION

Sustainability and energy supply are fundamental considerations for all concerned with the built environment. Governments, industry, academia, nongovernmental organizations and citizens have realized that we are using fuel at an exponential rate, damaging the environment in the process. To reduce global consumption of fossil fuels we need to do more with less and look to alternative sources of energy. The content of this chapter outlines the reasoning behind, and intention of this thesis.

1.1 Scope

Initiatives such as the U.S. Government Better Buildings Initiative to make commercial and industrial buildings 20% more energy efficient over the next 10 years have been developed to reduce fuel consumption and carbon emissions from the built environment (U.S. Department of Energy, 2013). New buildings can be designed to require very little thermal energy, relying on orientation, high levels of insulation and heat from localized solar thermal systems or district heating (The American Society of Heating, Refrigerating & Air-Conditioning Engineers (ASHRAE) Vision 2020 Ad Hoc Committee, 2008). Existing buildings can be retrofitted to substantially reduce fuel consumption with the addition of insulation, replacement of windows, and installation of efficient energy systems (Tabula Project Team, Institut Wohnen und Umwelt, 2012). The question becomes what can be done to improve the thermal energy storage of existing buildings that are historic or have a character or architectural merit that would be damaged with the addition of these typical solutions? Ireland has 38,171 protected structures (Murray, 2013) and thousands of structures that contribute to local and even national sense of collective memory and place. To maintain the value of these structures and improve energy efficiency, new technologies need to be developed.

An emerging area of thermal energy storage is Phase Changing Materials (PCM's). PCM's are materials that change phase when exposed to a temperature change. The material phase change can be solid–solid, solid–liquid and liquid–gas, solid–liquid PCMs are most suitable for thermal energy storage. PCM's are capable of storing and releasing large amounts of energy within specific temperature ranges over hourly or even seasonal periods. PCM's can be organic, inorganic or a mixture (eutectic) (Zhou, D., Zhao, C.Y., & Tian, Y., 2011), the classification of these materials can be seen in figure 1.1 Progress is being made in the testing and developing new building materials such as PCM-gypsum board, PCM-impregnated concrete, and PCM-enhanced fiber insulation, which provide new avenues for research and product development. Such materials have the potential to increase the thermal performance of construction elements and allow for sensitive retrofitting.

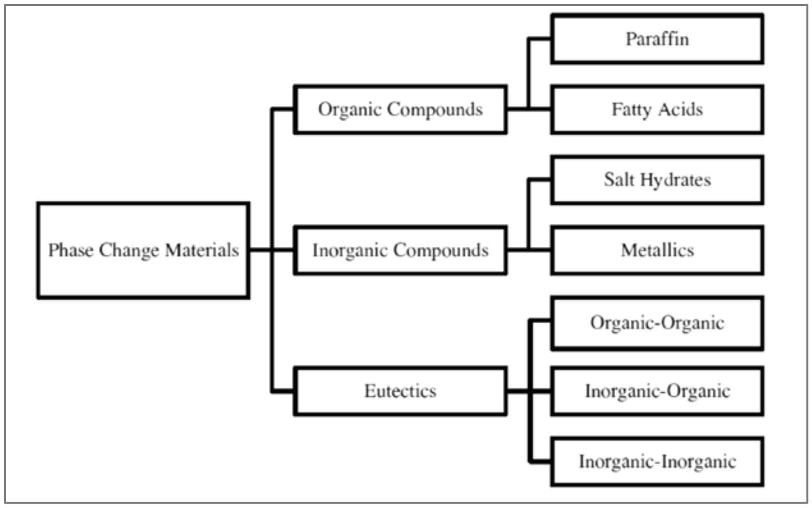


Figure 1.1 PCM's classification (Zhou, D., Zhao, C.Y., & Tian, Y., 2011)

The research called for an analysis of the potential and allowable applications for phase change materials (PCM's) to be used in buildings of significance. This was facilitated by a case study analysis of the possible improvement in thermal energy performance for Sligo Town Hall, Sligo, Ireland. The allowable applications for new materials were assessed through an analysis of applicable legislation both for the improvement of energy performance and for the protection of historic structures.

1.2 Significance

On the 9th of May 2013, the global concentration of CO2 in the atmosphere hit 400 parts per million for the first time, reiterating the message that CO2 levels are on the rise (National Geographic, 2013). It is believed by many that CO2 contributes to climate change and global warming, affecting ecosystems and causing dramatic climatic events. The continuing increase in concentration reflects global reliance on fossil fuels for heating, cooling, transport and construction. The conservation of energy in the built environment could reduce emissions and generate long term savings due to reduced fossil fuel consumption.

Concerns about climate change brought about the negotiation of The Kyoto Protocol, a legally binding treaty that sets out targets for reductions in emissions such as CO2. In response to the Kyoto protocol, the European Commission produced the Recast Energy Performance of Buildings Directive EPBD (Directive 2010/31/EU), which is designed as the overall framework for the improvement of energy performance in buildings. It addresses the energy requirements for lighting, ventilation, cooling, and space and water heating for new and existing buildings regardless of the type of building.

In the European Union, buildings account for 40% of total energy consumption and approximately 36% of the EU's CO2 emissions (EPBD Implementation Group, 2012). The implementation of Directive 2010/31/EU aims to reduce this figure and thus contribute to the overall reduction in energy use and CO2 production in Europe. Ireland must produce strategies to implement the new standards and introduce compliance by the end of 2018 for buildings in use by public authorities and all new buildings by the end of 2020.

The idea of a building being used without the need for a supplementary energy source is known as a Zero Energy Building (ZEB). It is no longer a concept; it is the solution for the mitigation of CO2 emissions from buildings. PCM materials have the potential to bridge the gap in thermal efficiency between such new building methods and retrofit construction. Retrofit construction of historic buildings is subject to strict controls as the building aesthetics and ability to 'breathe' cannot be compromised. New construction utilizes substantial wall insulation and strives to be 'airtight' to reduce heat loss.

The benefits of the application of PCM heat management technologies would include increased sustainability of the national building stock due to a reduction in energy consumption and carbon emissions. The functionality of the buildings would be increased as a comfortable occupant temperature would be more easily obtained. Finally an increased range of products for improving thermal energy performance would allow for sensitive and sophisticated retrofitting of buildings with architectural, historical or even sentimental value.

1.3 Statement of Purpose

The purpose of this research was to analyze the relevant legislation governing historic structures, examine the properties of phase changing material (PCM) technologies, and evaluate the potential for PCM technology to improve the thermal performance of older structures. The improvement of building thermal energy performance ensures the functionality and protection of existing structures, thereby increasing the overall sustainability of the built environment and the potential for the preservation of social capital and continuity.

A single nationally protected structure was chosen in Sligo, Ireland, and national, European and international legislation was analyzed in order to assess the areas of structures with historical significance, which could be sensitively retrofitted. This research will expand the knowledge of retrofitting with PCM technologies and put forward information on how they might be successfully integrated in similar contexts. Additionally this research identified the potential benefits of such integration with particular reference to thermal comfort, energy savings, and sensitivity to the structure.

1.4 Research Question

The main question central to this research was:

- Can the central heating system of Sligo Town Hall, Sligo, Ireland, be retrofitted with phase changing material slurry to improve thermal energy performance? What would be the estimated percentage improvement and payback period?

1.5 Assumptions

The assumptions for this project include:

1. The requirement that historical buildings should be maintained to the highest standard and protected from damage and alteration.
2. Sustainability and energy efficiency are necessary considerations for the built environment and it is beneficial to develop new technologies to facilitate energy conservation.
3. Sligo Town Hall, Sligo, Ireland would benefit from an improvement in its thermal energy storage.

1.6 Limitations

The limitations for this project include:

1. The chosen building for case study analysis is restricted; as a result a substitute building will be used for data collection.
2. The influence of weather cannot be removed from the study.
3. The influence of heat sources not controlled as part of this research cannot be removed.
4. The researcher will interpret the data in this study. Human error, bias, and deficits in the researcher's knowledge may not be entirely mitigated or removed.

1.7 Delimitations

The delimitations for this project include:

1. Test will be limited to the analyzing of microencapsulated phase change material slurry only.
2. The study concerns Sligo Town Hall, Sligo, Ireland, designed circa 1865 by William Hague, and a domestic house at Rossinver, Co. Leitrim, Ireland, built circa 1810.
3. Results and conclusions of this study are specific to solid stone construction buildings in temperate climates, and cannot be considered generalizable to all buildings. Different types of building construction and climate will affect the energy usage and thermal capacity.
4. No physical change will be made to either building structure in the course of this study.

5. The movement of heat through convection, conduction, or radiation, in the test room or in the test fluid will not be studied.
6. No energy modeling software will be used in this study.
7. Descriptive statistics will be performed using SPSS, a statistical analysis software package by IBM.

1.8 Definitions

Directive 2010/31/EU, Recast Energy Performance of Buildings Directive (EPBD) : EU Member States must make new and retrofitted buildings nearly-zero energy by 2020 (Concerted Action EPBD, 2013).

Executive Order 13514, Federal Leadership in Environmental, Energy, and Economic Performance: United States Environmental Protection Agency directive which requires all federal buildings to be designed to achieve zero net energy use by 2030 and 15 percent of existing buildings and leases meet the Guiding Principles by 2015 (Environmental Protection Agency, 2009).

Phase changing materials (PCM's): materials that change structure from solid–solid, solid–liquid, solid–gas and liquid–gas states at specific temperatures. PCM's are capable of storing and releasing large amounts of energy over hourly or seasonal time period's (Boyle, 2004).

Microencapsulated PCM slurries (mPCM slurries) consist of PCM particles covered in a layer of polymer in a conductive fluid such as water. (Inaba, 2000)

Thermal Energy Storage (TES): storage of excess thermal heat for use at a later stage (Boyle, 2004).

1.9 Summary

This chapter outlined the reasoning behind, and intention of this thesis. It provided details on the scope, significance, and statement of purpose for the study. The research question was defined and the main assumptions, limitations, and delimitations were outlined along with key definitions.

CHAPTER 2 REVIEW OF RELEVENT LITERATURE

Three areas of existing research are discussed in this literature review; sustainable development and the protection of historic structures, thermal energy storage and thermal comfort, and thermal energy storage (TES) and phase changing materials (PCM's). These topics were chosen to provide a strong understanding of the challenges associated with sensitive retrofitting and the potential benefit of using phase changing materials technology.

2.1 Literature Review and Methodology

Understanding of thermal energy storage goes back to the earliest origins of humankind. Traditional thick walled earth structures insulated, and protected the inhabitants from contextual extremes of hot and cold, and temperature swings from day to night. People made the most of the natural characteristics of available materials relative to local climate in order to improve their daily life and thermal comfort. Researchers have developed an extensive knowledge of material thermal capacities and strategies for thermal management and associated issues.

The literature presented in this review examines the need for sustainable construction and renovations. It argues the reason why we should retain our historical structures, and documents what legislation exists to ensure vulnerable buildings are protected. The research considers the fundamentals, benefits, and drawbacks of thermal energy storage as well as accepted strategies in thermal energy storage. This provides a basis for a discussion of phase changing materials and construction, including what are phase changing materials and what are their capabilities.

2.2 Search Areas for Literature Review

Providing the most suitable research requires a broad spectrum of research types and sources. The arguments for retention of historic buildings is both phenomenological and factual, while journal articles based on quantitative research are more empirical. The research in this literature review crosses many disciplines, meaning that the research does not come from one particular information source. Sources include journal articles, books, government acts and directives, theses, and websites.

Specific methods for the collection of information for this thesis included online sources; Google Scholar, Google, YouTube, and twitter; discussions with researchers in the field, specifically the attendees of the COST Training School on ‘Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings (NeCoE-PCM)’ which took place between the 15th to 17th of April 2013 in Dublin Institute of Technology, Ireland, and the library resources and online database provided by Purdue University, West Lafayette, Indiana, U.S.A.

Search terms included but were not limited to: historic buildings, nationally protected structure legislation, strategies for energy saving, energy efficient buildings, retrofitting buildings, thermal energy, thermal comfort, phase change materials, phase change material slurry, research methodologies, and case study research.

2.3 Sustainable Development and the Protection of Historic Structures

With the advent of combustion heating systems and air-conditioning, the thermal energy storage capability of building structures decreased due to an abundance of fossil fuel. Since the oil embargo imposed by the Organization of Arab Petroleum Exporting Countries (OAPEC) in 1973, energy security concerns and increasing concern about the damage caused by combustion emissions such as carbon dioxide to the environment, have increased the research on security of energy supply and sustainability of use. There are a number of definitions of sustainability, probably the most frequently used is from the World Commission on Environment and Development, Brundtland Commission 1987 which states; *"Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* World Commission on Environment and Development (1987, p. 45). This is a humanist definition, meaning that we should manage our resources so that developing countries can develop, and wealthy nations can maintain living and economic standards.

2.3.1 Kyoto Protocol

According to Tollefson (2011), the Kyoto Protocol describes commitments by wealthy nations to reduce the emission of greenhouse gases. Deliberated originally in 1997 in Kyoto, and subsequently in 2009 in Copenhagen, the agreement aims to produce a global strategy to mitigate damage caused by the use of fossil fuels. The United States never ratified the Kyoto Protocol and since then has been on-going debate on the value of the treaty. Issues associated with the agreement include wealthy nation's previous pollution and developing countries now being the world's largest polluters.

Cracks in the protocol appeared in Copenhagen when Japan, Canada, and Russia, who had originally agreed to meet the protocol opposed a second commitment. This meeting of nations ended with little formal commitment, but countries agreed to voluntary commitments to reduction. China, Brazil, and South Africa agreed to reduce emissions in exchange for increased funding for developing nations dealing with global warming and climate change. Commitments fell short of what was considered necessary by the United Nations to halt the increase in temperature (Tollefson, 2011).

2.3.2 Kyoto Holds On

Despite concerns over commitment to the targets and disagreements between nations, the Kyoto protocol survived the 18th United Nations conference on climate change in Doha, Qatar (Marshall, 2012). Approximately 200 nations attended and agreed to extend the protocol for seven years to 2020. The agreement proposed to establish a U.N. technology centre to help developing nation's lower emissions and manage climate change impact. Wealthy countries however delayed a plan to provide poorer nations up to $100 billion dollars a year in climate aid by 2020 (Marshall, 2012). The United States maintained its exclusion and Japan, Russia and Canada dropped out. This renewed protocol only covers about 15% of the countries responsible for global emissions. According to Marshall (2012) delegates are hopeful more countries will join.

2.3.3 Significance of Older Buildings

The significance of older buildings is discussed by Gelfand and Duncan (2012) in their book *Sustainable Renovation, Strategies for Commercial Building Systems and Envelope*. They observed that early sustainability was concerned with air and water pollution, and habitat protection, and that now focus has shifted to carbon and energy action. Originally, factories, vehicles, and city sewage were targeted for cleanup, but now the existing building stock is under scrutiny.

> Major contributors to greenhouse gas emission are tied to the building sector, including producers of electricity and heat, land use change, and industry (production such as iron, steel and cement). Reducing these contributions requires reducing building energy use during operation (electricity, heat, cooling), reducing use of high energy construction materials (reusing existing buildings, using low-impact materials), and reducing sprawl that paves over productive land (Gelfand & Duncan, 2012, p. 4).

The authors propose that changing our existing building stock has the potential to alleviate our carbon footprint, undoing some of the ongoing damage created by day to day living. “Great renovations begin to heal the planet” (Gelfand & Duncan, 2012, p. 6).

2.3.4 Sustainable Renovation Strategies

Society and buildings have an ever escalating need for energy. The way we design has changed over time and sustainable renovation strategies need to reflect this. “A prewar building designed for natural daylight, natural ventilation, and characterized by high thermal mass, often has more need for its old logic to be restored in a renovation than to be completely rethought. Later buildings become more and more dependent on oversized mechanical systems and cheap electric lighting and their shapes and envelopes changed as well” (Gelfand & Duncan, 2012, p. 7). There are different challenges associated with buildings of different eras but strategies can be developed for different periods of construction.

Gelfand and Duncan (2012) identify three phases of intervention that could be used as a strategy for the renovation of buildings. The first is minimal intervention where energy management is the primary method of improvement. The second is the replacement of old building systems and the third is a significant renovation, which would involve a reevaluation of the buildings use, its systems and its construction. The authors argue against demolition, noting that there needs to be a critical evaluation of the building’s viability. Gelfand and Duncan (2012, p. 9) quote from the United Nations

Environment Programme (UNEP) publication *Buildings and Climate Change-Status, Challenges and opportunities*, “The embodied energy of a building created during its construction accounts for 10 to 20 percent of the energy consumed by the building over its entire existence” (Huovila, Ala-Juusela, Melchert, & Pouffary, 2007, p. 7).

According to the authors, the decision to replace a building should adhere to the following criteria:

- “The total energy used in demolition and waste disposal of the existing building plus construction and operation of the new building will save more energy than the energy used in renovating and operating the existing building.” (Gelfand & Duncan, p. 9)
- “It will have additional benefits in increasing the sustainability of the site and local community.” (Gelfand & Duncan, p. 9)
- “The components of the existing building can be productively used.” (Gelfand & Duncan, p. 9)

2.3.5 EU Directive on Sustainable Development

In considering the move to sustainable development, it makes sense to consider the strategies of governments for the implementation of positive change. Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast) targets the built environment explicitly. The directive deals with the setting of energy performance standards, calculating building energy performance standards, existing buildings, new buildings, nearly zero energy buildings, building alterations, buildings systems, and financial incentives.

Delivered in response to commitments made in the Kyoto protocol, the European Commission produced the Energy Performance of Buildings Directive (EPBD) in 2002, which is the overall framework law for the implementation of energy performance in buildings in the 28 member states. Directive 2010/31/EU known as EPBD (recast) of May 2010 amends the existing legislation with substantive changes to help honor the United Nations Framework Convention on Climate Change. This comprehensive document stipulates in Article 3 that the EU will reduce CO2 emissions by 20% on the 1990 levels by 2020. This is known as the (20:20:20) vision (The European Parliament and the Council of the European Union, 2010).

The European Parliament and the Council of the European Union (2010) acknowledges that buildings are responsible for 40% of the total energy used in the EU. It notes that public authorities need to lead by example, developing and enforcing changes to the buildings regulations. The document identifies the need for the application of minimum requirements to the energy performance of new buildings, existing buildings, and major renovations. It notes that financial instruments need to be provided to encourage or stimulate implementation. Energy performance certification for non-residential buildings is to be publically displayed and information on actual energy consumption calculated and available for inspection.

Preparation of national plans that promote the building of near Zero Energy Buildings (nZEB), which are buildings with very low energy requirements provided from renewable sources produced locally. The document requires increased use of renewable energy sources and notes alternative carbon neutral energy supplies must be explored, having first ensured that energy consumption requirements are reduced to optimum cost levels (The European Parliament and the Council of the European Union, 2010)

2.3.6 USA Energy Independence and Security Act of 2007

Many nations are implementing policies and incentives to increase sustainability. Although investment is required, sustainable strategies for national sustainability can generate revenue, support job creation, and stimulate innovation. The analysis of the Energy Independence and Security Act of 2007 is necessary to identify the main government strategies for increased energy savings in the built environment of the United States. Within the area of buildings and the built environment, the act covers energy savings in residential, governmental, and industrial buildings.

The Energy Independence and Security Act of 2007 (H.R. 6. 110th Congress, 2007) has a particularly strong objective for the building stock in the United States. It stipulates that by 2030 federal buildings be designed to achieve "zero net energy", meaning that buildings will not consume any more energy than they produce. The zero net energy commercial buildings are defined in Article 3 as “A high performance building that is designed, constructed and operated to require a greatly reduced quantity of energy to operate, to meet the balance of energy needs from sources of energy that do not produce greenhouse gases, in a manner that will result in no net emissions of greenhouse gases and to be economically viable” (H.R. 6. 110th Congress, 2007, p. 45).

Residential building efficiency will be improved through the allocation of funding for consumer grants. Energy code improvements applicable to manufactured housing will establish standards for energy efficiency, and there will be a review of rebate energy programs established under the Energy Policy Act 2005. The intentions are to (a) "To reduce the quantity of energy consumed by commercial buildings located in the United States" and (b) "To achieve the development of Zero Net Energy commercial buildings in the United States" (H.R. 6. 110th Congress, 2007, p. 46).

2.4 Sustainable Design and Zero Energy Buildings (NZEBs)

"Buildings consume 40% of the primary energy and 71% of the electrical energy in the US" (ASHRAE Vision 2020 Ad Hoc Committee, 2008, p. 4). ASHRAE's aspirations are that by the year 2030 net zero energy buildings (NZEBs) will be affordable and commonplace. This system is primarily aimed at new buildings although the authors note it could feasibly be used on existing buildings. According to the ASHRAE Vision 2020 Ad Hoc Committee (2008):

> A NZEB is a building that produces as much energy as it uses when measured at the site. On an annual basis, it produces or consumes as much energy from - renewable sources as it uses while maintaining an acceptable level of service and functionality. NZEBs can exchange energy with the power grid as long as the net energy balance is zero on an annual basis. (ASHRAE Vision 2020 Ad Hoc Committee, 2008, p. 4)

Definitions for nZEB's vary depending on the energy body concerned. The National Renewable Energy Laboratory (NREL) discus the definition of nZEB in depth and describes four ways to define net zero energy; net zero site energy, net zero source energy, net zero energy costs, and net zero energy emissions (NREL, 2006). Most bodies agree however that nZEB's should have very high quality design that minimizes energy requirements and they should have renewable energy systems that can meet the buildings energy needs (Steven Winter Associates, 2014).

Steven Winter Associates illustrates some of the fundamental aspects of nZEB's for the National Institute of Building Science's Whole Building Design Guide. The authors note that energy efficiency can be achieved through high performance envelopes, daylighting, sun control, shading, and air barrier systems. These design strategies are generally considered cost effective with a high ratio of return on investment. Renewable energy sources can be onsite or offsite. Onsite may include wind turbines, solar water heating, photovoltaics (P.V.), and biomass. Offsite energy may refer to the use of land at another location due to site restrictions but more commonly refers to the purchasing of renewable energy credits (REC's) from large scale renewable energy utility providers such as wind farms and solar plants. While nZEB's have renewable energy sources they are generally connected to the grid. Onsite energy supply systems may not produce enough energy at peak demand but could create a surplus at other times, balancing out the buildings energy use over the course of a year.

These buildings do not consider the embodied energy of the building construction. The feasibility of this plan to design buildings with net zero energy usage relies on sophisticated engineering of mechanical systems and building envelope. ASHRAE Vision 2020 Ad Hoc Committee (2008) identify a number of areas that are central to NZEB design. The first is full integration of systems so that 'waste energy' from different processes is not lost. Energy should be recouped from all available sources. This would apply in particularly to ventilation and heating where heat exchangers and combined heat and power (CHP) units are used. The authors note that efficiency of systems is very important. It is envisaged that systems would be highly efficient and smaller than traditional systems, would adapt to variations in external temperatures, and would separate cooling from dehumidification and moisture control. The ASHRAE Vision 2020 Ad Hoc Committee (2008) notes that net zero energy buildings would be more responsive due to greater sensor integration, sensing temperature, air moisture content, motion, and daylight levels. The authors propose membership and training courses for individuals and a building certification system as utilized in Europe.

Such a system requires controlled ventilation to ensure energy efficiency and good indoor air quality, meaning ventilation is not controlled by occupants but by an automated system. There are many benefits as outlined by ASHRAE such as heat recovery but there are potential issues that can arise such as occupant discomfort with inoperable windows, and the continued maintenance of air filtration systems.

Giuseppe (2013) warns that the airtightness of the nZEB environment may result in high internal moisture levels leading to surface condensation and biological growth. Externally, new organic renders and paints are also vulnerable to mold or algae growth due to 'thermal de-coupling'. According to Giuseepe (2013) the lower surface temperature of the building façade in the evening due to a lack of heat loss increases condensation on the surface earlier and for longer than on traditional building facades.

2.4.1 TABULA, Classification of Existing Buildings in Europe

Tabula is an Intelligent Energy Europe project that is working to coordinate and gather information on the renovation of buildings in Europe in accordance with the EU Directive 2010/31/EU. The Tabula system is currently being developed in 15 European countries including Ireland. The objective of this system is to gather all useful information on retrofitting domestic buildings for energy conservation into one place. The accumulated data can then be used as a reference for designers and homeowners who want to increase the sustainability of their homes (Tabula Project Team, Institut Wohnen und Umwelt, 2012)

The Tabula Project Team, Institut Wohnen und Umwelt (2012) identified common building types and identified potential strategies for upgrading. It focuses on space and water heating, with the aspiration that retrofits can be successful, member states can learn from each other, and governments have a tool for implementing and encouraging change.

> An overview of the national building typology is given by the "Building Type Matrix”. The columns of the matrix represent four building size classes (single-family houses, terraced houses, multi-family houses, apartment blocks), the rows a certain number of construction year classes. The start year and end year of the construction year classes are individually defined for each country. The single

cells of the matrix form the generic "Building Types" of a country (Tabula Project Team, Institut Wohnen und Umwelt, 2012, p. 8)

2.4.2 The Challenge of Successful Renovation

Renovation has the potential to significantly reduce the quantities of carbon dioxide being produced in wealthy countries. Increasing insulation, increasing airtightness, providing sustainable energy sources, optimizing solar gain, installing efficient devices, and increasing user management skills are the key factors required to optimize thermal comfort and sustainable design (Thorpe, 2010). Designers need to be educated on the appropriate use of sustainable strategies and technologies otherwise renovations will not work.

Thorpe (2010) notes there are many examples of poor integration of new technologies creating a mismatch between production and use, this has led to inhabitants returning to public supply for electrical heating. Insulation can cause excessive mold growth and petrochemical-derived insulants produce carbon dioxide during the manufacturing phase (Thorpe, 2010).

Thorpe (2010) illustrates that designers must be wary of the blanket approach illustrated in building standards and manufacturer’s promises of reductions and savings. Optimal improvement in thermal comfort and energy efficiency requires a whole building approach, unique to that particular building.

Historic buildings have more at stake when it comes to retrofitting for energy efficiency. The strategies and technologies for new and existing buildings are still being developed and tested. There are no simple answers and there have been many mistakes made. The upgrading of buildings requires a whole building approach, where renewable energy sources, ventilation, moisture, heating, lighting, orientation and materials are all interlinked. If the system is not well designed there can be a mismatch leading to waste and inefficiencies (Thorpe, 2010).

The most recognized approaches to upgrading of a buildings thermal capacity is to reduce or eliminate draughts, upgrade appliances, increase the insulation, maximize useful solar gain, and minimize overheating (Tabula, 2012). Historic buildings need a different approach.

Widström (2012) explored the challenges associated with creating a modeling system for historic buildings in Sweden in his thesis written as part of the multidisciplinary project, *Energy Efficiency and Preventive Climate Control*, which was ran by the Swedish Energy Agency among a number of universities in 2012 with the intention of providing guidelines and methodologies for the simulation and actual restoration of historic buildings in Sweden. The author notes that:

> We need to recognize that the energy performance of the building is intimately related to several other domains, most prominently moisture performance and use of the building. This is the case in modern buildings as well, but in the historical buildings it becomes both more emphasized due to often much larger moisture exchange as well as more differentiated use, and at the same time the sensitivity of the buildings and their inventories make the stakes higher, should a less suitable retrofitting strategy be chosen (Widström, 2012, p. 5).

The study analyses all the elements that influence the internal environment of a historical building such as lack of use, and an unavailability of skilled individuals and suitable materials. Often the external façade is protected; limiting the addition of insulation to the interior of the building, which when combined with high internal temperatures can lead to problems with moisture build up, damaging the structure and potentially impacting on building artifacts such as paintings (Widström, 2012).

Historic buildings need a considered and a sensitive approach to retrofitting. Often the options for alteration to the structure will be minimal so it is necessary for new technologies to be developed to work with the existing properties of the structure to maximize thermal comfort and energy efficiency whilst maintaining the character and integrity of the structure.

2.4.3 Hygrothermal Performance

Understanding moisture movement is critical in the development of renovation strategies for historical buildings. In the drive to improve energy efficiencies, modern glazing, polystyrene insulation, and vapor barrier membranes have been installed in old structures. These well intentioned interventions then lead to mold growth, crumbling brickwork, and bubbling plaster. Giuseppe describes an example of the replacement of single glazed windows with double or triple glazed windows resulting in condensation as ventilation is reduced and new thermal bridges are made on the frames, subframes and structure.

> All these measures, if on the one hand greatly increase the energy performance of buildings, could on the other hand determine new ways of heat and moisture exchange in the building envelope which are extremely different from those of traditional building envelopes, we have always been accustomed to. (Giuseppe, 2013, p. 61)

Increased focus is being placed on understanding moisture movement in order to ensure appropriate strategies are implemented. The way moisture moves in historical buildings is considerably different than in modern construction as discussed by Little. He notes that there are more liquid movements in solid stone walls and less air circulation to remove it. The structure must be allowed to 'breathe', meaning that water liquid and water vapor need to be allowed to move through the fabric. The movement of water vapor and air can be seen in figure 2.1.

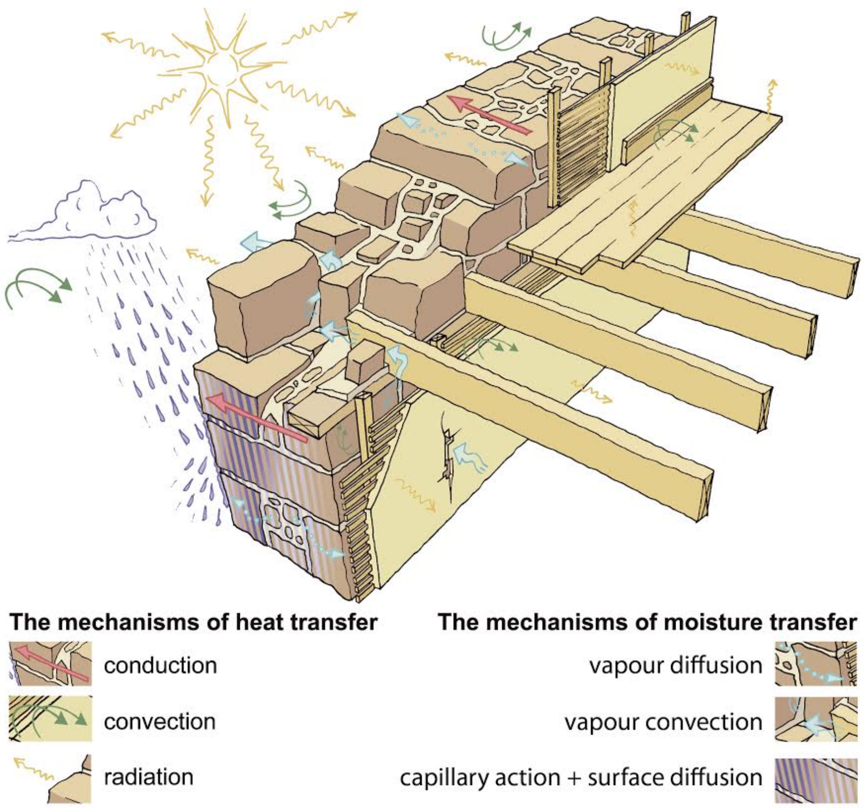


Figure 2.1 Moisture behavior in traditional walls (Little, personal communication, September 7, 2015)

Air with a high relative humidity (RH) can turn to condensation if it comes into contact with a surface at a cooler temperature than the air. As the contacting air cools it reaches its dew point and condensation forms. Constant high humidity encourages the growth and spread of mould. If a building is not heated sufficiently the humidity in any warmed air will condense during heating and cooling cycles, potentially moving to unheated rooms causing dampness (Littlefield, 2008).

The risk of surface condensation can be calculated using a psychrometric chart which considers relative humidity, and external and internal temperatures. Reducing surface condensation requires a balance of heating, ventilation, insulation, and an understanding of moisture production by occupants and building processes. (Littlefield, 2008)

Moisture has the ability to move through materials, the ease of this is based on the vapor resistance of the material, the vapor pressure of the air, capillary suction and liquid moisture transfer (Littlefield, 2008). Little (2011) explains in more detail that that vapor pressure is the driving force behind vapor transfer and that porous material's such as stone have capillaries which can store and assist in the movement of moisture.

> This movement of liquid water is called capillary action and is commonly described as wicking. It can also be moved there by suction (during diving rain or rising damp) and redistribution transports (when sun or heating system dries). The higher the relative humidity the thicker the layer of liquid water.
> (Little, 2011, p. 7

The presence of moisture in the external envelope can lead to aesthetic and structural problems. Water vapor in the walls can become liquid if the temperature within the wall falls below the dew point temperature. This liquid can create a freeze and thaw cycle in winter which causes bricks and mortar to crumble.

2.4.4 Thermal Energy Storage and Thermal Comfort

The value of good thermal energy storage goes beyond the reduction in energy usage, and protection of a structure from mold and climate influence. The comfort, health, and 'delight' of occupants should also be considered according to Nicol, Humphreys, and Roaf (2012). Comfort is important to occupants and air temperature in combination with air freshness impacts the inhabitant's perception of the space. Delight can come from a fresh breeze on a hot day or an equilibrium between core body temperature and surroundings.

Nicol, Humphreys, and Roaf (2012) also note that health is influenced by extremes in temperature, and climatic change has increased the incidence of very hot summers and very cold winters leaving the vulnerable and those dealing with fuel poverty at risk. "A person or family is said to be in fuel poverty in the UK if more than 10 percent of their disposable income is required to ensure a comfortable temperature in their home….by the summer of 2011 around 35 percent of all homes in Scotland were deemed to be in fuel poverty" (Nicol, Humphreys & Roaf, 2012, p. 4).

In regards to energy consumption, the outside temperature greatly influences readings. Nicol, Humphreys, and Roaf (2012) note that the number of 'heating degree-days' is an important consideration in calculating heating and cooling loads. Calculated from weather data, this data can help designers calculate the most appropriate heating system and infer whether existing systems are being used efficiently. Degree days are "…found by multiplying the days during which there is an indoor-outdoor temperature drop by the number of degrees temperature drop for each day" (Nicol, Humphreys, & Roaf, 2012, p. 5)

According to Nicol, Humphreys, and Roaf (2012), people have different temperature expectations depending whether it is winter or summer, and this varies from country to country. There are significant differences between the European and

United States systems for heating and cooling. The authors note that the United States relies heavily on air-conditioning to manage the air quality and temperatures of buildings, while in Europe, natural ventilation and solar gain are more commonly used. The proliferation of air-conditioning has led to the creation of buildings that use high levels of electricity, which is an expensive output of fossil fuel combustion. It is noted that changes to envelope and management in air-conditioning dependent buildings can allow for reduced mechanical intervention (Nicol, Humphreys, & Roaf, 2012).

Littlefield (2008) also discusses thermal comfort levels in the Metric Handbook Planning and Design Data, the author notes it is very difficult to design a situation where an optimum temperature will be reached for everyone. Using Fanger's comfort equation which is based on extensive studies and uses predicted mean vote (PMV) and percentage people dissatisfied (PPD) the author surmises that five percent of people in a group will report discomfort. These people will then adapt to their environment through clothing, activity and posture.

Guidelines on air temperatures vary on building typology, and within each typology different rooms will have different needs, offices can range from 21-23^{o}C, hospitals require 22-24^{o}C, schools function between 19-21^{o}C, and art galleries and museums use a range of 19-21^{o}C (Littlefield, 2008).

Ideally buildings would function purely by non-mechanical means to reduce building energy consumption. Careful orientation, thermal mass, insulation, natural ventilation and considered glazing are elements of good design for thermal comfort.

"Thermal comfort is influenced by air temperature, air movement, relative humidity and surrounding radiant environment" (Littlefield, 2008, p. 39-2)

Littlefield (2008) describes thermal design as passive or active. Passive thermal design considers fabric, orientation, and building form while active thermal design relates to mechanical devices. A combination of these methods may be required to ensure thermal comfort and high quality passive design may eliminate the need for mechanical devices or reduce the size and energy input requirement of HVAC Systems. Thermal capacity is an important strategy used in passive design. Buildings which are lightweight such as timber frame construction, have little thermal capacity and are quick to heat up and cool down meaning they are likely to overheat in hot weather and be quite cool in colder weather. This kind of construction requires a very responsive heating and cooling system, often heating and cooling in the same day to manage temperature fluctuations. Heavyweight buildings such as stone buildings are slow to respond to external temperatures, they have a high thermal capacity which helps maintain a more stable internal environment. A sample profile of thermal responses for lightweight and heavy weight buildings can be seen in figure 2.2.

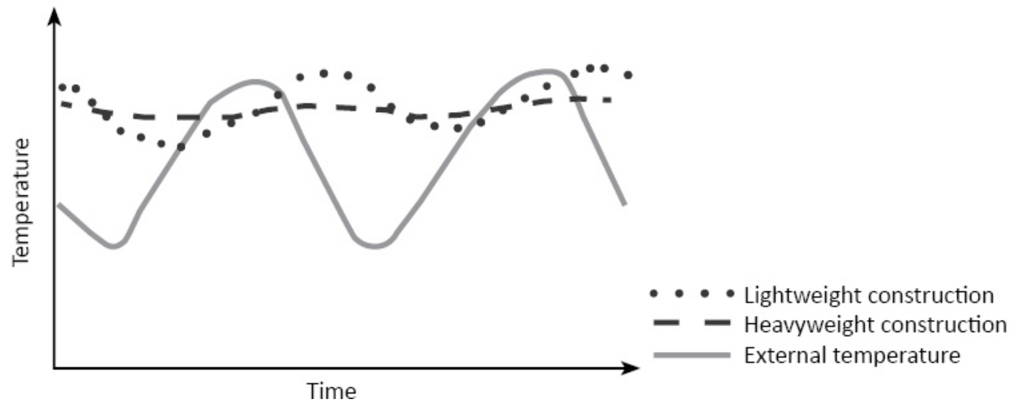


Figure 2.2 Thermal response of heavyweight and lightweight construction against external air temperature.

Nicol, Humphreys, and Roaf, (2012) discuss the variability of thermal environments that can exist in a building and suggest that current standards create one standard temperature, whereas traditional buildings used a variety of thermal environments to provide inhabitants with a reasonable level of comfort without substantial resource dependency. In discussing variability and adaptive thermal comfort, the authors surmise that

> The relationship between people and environment is complex and active, bringing in time, climate, building form, social conditioning, economic and other factors as well as the immediate physical environment…This (variability) means an indoor environment that changes with the season and the climate, that allows buildings to change, suggests how quickly they should do so and reflects willingness of occupants to vary their environment by returning some measure of control to them (Nicol, Humphreys, & Roaf, 2012, p. 7)

Nicol, Humphreys, and Roaf (2012) suggest an adaptive approach to providing the optimal thermal environment, reflective of user surveys and post-occupancy studies. The authors criticize architects for leaving thermal design to mechanical engineers undervaluing the thermal comfort of the inhabitants. Adaptive principle notes that despite all mechanical intervention "If a change occurs as to produce discomfort, people react in ways which tend to restore their comfort." (Nicol, Humphreys & Roaf, 2012, p. 8) leading to disconnected systems and returns to unsustainable electrical heating systems.

2.5 Thermal Energy Storage (TES) and Phase Changing Materials (PCM's)

A potential method for managing internal thermal comfort and energy efficiency is the application of thermal energy storage (TES) systems. According to Zhou, Zhao, and Tian (2011):

> Thermal energy storage can be generally classified as sensible heat storage and latent heat storage according to the heat storage media. In sensible heat storage, the heat is stored or released accompanied with temperature change of the storage media, whereas in the latent heat storage the heat is stored or released as heat of fusion/solidification during phase change processes of the storage media (p. 2).

The focus of this thesis will be on the potential of latent heat storage rather than sensible heat storage. In sensible heat storage a material heats up at a constant rate as thermal energy is applied, water storage tanks is the most common form of sensible heat storage. In latent heat storage the material heats up as thermal energy is applied but it does not have a smooth rate of increase as it absorbs more thermal energy. The two types of heating are illustrated in figure 2.3. According to Pasupathya, Velraja, and Seenirajb (2008):

> In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of stored thermal energy depends on the specific heat of the medium, the temperature change and the amount of storage material. LHS is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice-versa.

Latent heat storage has the potential to store large amounts of thermal energy in a small area, with the benefits of little change in the volume of the material and temperature of the substance. Latent storage can be used in passive systems or active systems for heating and cooling of buildings, meaning there is potential for this technology to be used in variety of climates and building styles.

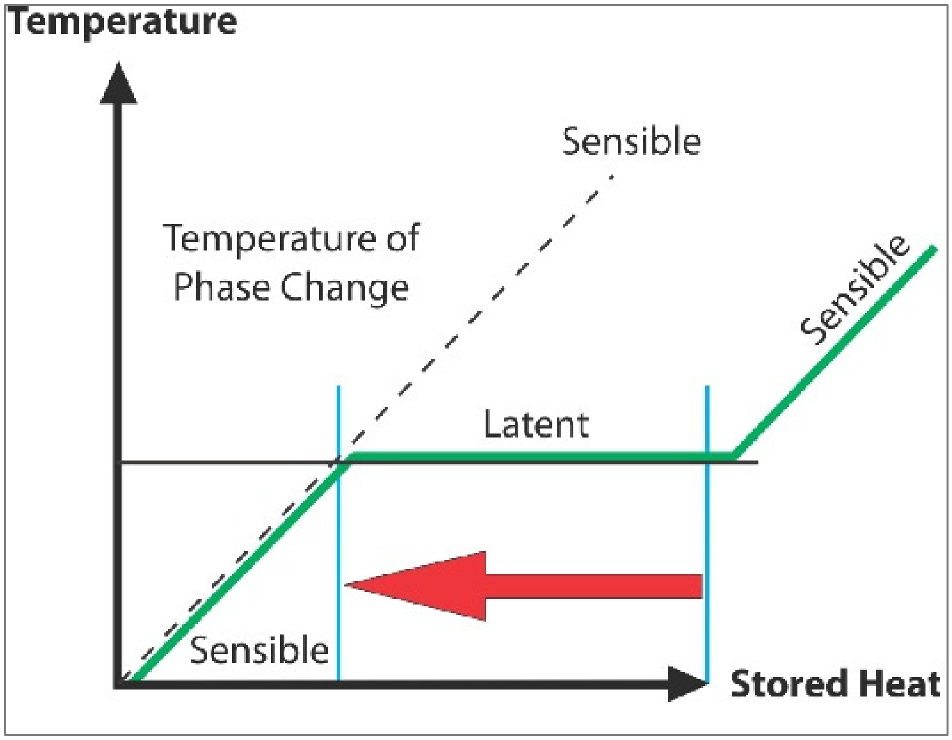


Figure 2.3 Sensible heat plotted against latent heat (RGEES, 2014)

2.5.1 Phase Changing Materials

An article entitled *Materials used as PCM in thermal energy storage in buildings* by Cabezaa, Castell, Barrenechea, de Graciaa, Fernández (2010) attempts to gather the main information on PCM's. The article details the technology requirements, how the materials are classified, and potential problems and opportunities associated with their use. PCM materials can be classified in two categories, organic and inorganic. There are different advantages and disadvantages for both types, which relate to their melting temperatures, heat of fusion, thermal conductivity, and density. PCM can be incorporated into building materials such as concrete, plasterboard, and plaster. Not only that, it can be combined with heating and cooling systems.

The authors identify certain challenges associated with the use of PCM's such as the stability of the PCM-container over an extended period. The container must be able to withstand the small change in volume, the change in chemical composition, and it must be a good conductor to maximize system efficiency. A very specific issue of phase changing materials are segregation and subcooling.

Segregation is described by Cabezaa et al. (2010) as occurring when the heavier material particles sink over time, impacting substantially on efficiency. Subcooling is described as the point when the material starts to solidify at a temperature lower than its hardening temperature. This phase between solid and liquid impacts the conductivity of the material.

2.5.2 Testing of PCM Systems

Caliskan, Dincer, and Hepbasli (2011) demonstrated that PCM based thermal energy storage can reduce the heating load of a building. They proposed a combined study of three heating systems, thermochemical, latent, and sensible. Heating system one consisted of a latent, fan assisted thermal energy storage wall system. The building envelope comprised of an external layer of glass, transparent insulation material, PCM, an air channel, and an internal layer of insulation, see figure 2.4. The latent heat study concerned one particular PCM called "Rubitherm RT-27," which is comprised of paraffin and waxes. The solar radiation passed through the glass and transparent insulation to the layer of PCM. The PCM absorbed the energy and later released it when air was pumped through the adjacent cavity and then into the room. The authors reported an increase in the air temperature from 9-11°C to 21.5-23.5°C, see figure 2.5. The provision of this warm air resulted in a reduction in the space heating load from the thermochemical and sensible heating systems also installed. The authors noted that while it was helpful, the energy generated by the PCM in this particular system setup was low in comparison with the energy generated by the other two systems.

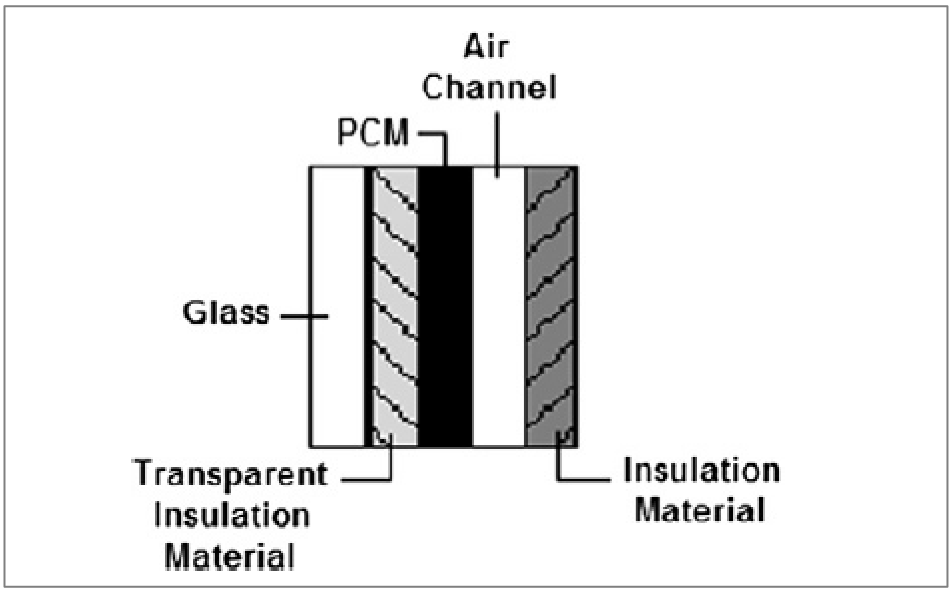


Figure 2.4 A schematic of the PCM filled wall (Caliskan, Dincer, & Hepbasli, 2011)

Specification	Value
Total volume of the PCM	4.01 m^3
Utilization time of the PCM	7.22 h
Glass area	58.801 m^2
Solar radiation	800 W/m^2
Temperature of the interior surface of the glass	16 °C
Phase change temperature of the PCM	28 °C
Temperature of the PCM at the end of the process	41 °C
Mass flow rate of the air	0.14741 kg/s
Temperature of the inlet air at the air channel	9–11 °C
Pressure of the air at inlet and outlet of the air channel	101.325 kPa
Temperature of the outlet air at the air channel	21.5–23.5 °C
Specific heat of air	1.005 kJ/kg°C
Relative humidity of the air at inlet of the air channel	50%
Relative humidity of the air at outlet of the air channel	22.41–22.8%
Sun temperature	6000 K
Specific heat of the water vapor	1.872 kJ/kg °C

Figure 2.5 Data of the latent heat energy storage system (Caliskan, Dincer, & Hepbasli, 2011)

2.5.3 Benefits of Phase Changing Materials

Two areas of particular interest to building system designers and building designers are free cooling and peak load shifting. Free cooling can be described as cooling of PCM materials with low external air for air-conditioning and industrial purposes (Zhu, Ma, & Wang, 2009). The authors found that “the application of PCMs for free cooling in buildings is subjected to local climate conditions. A large temperature difference between day and night is favorable for free cooling applications” (Zhu, Ma, & Wang, 2009, p. 11). Peak load shifting relates to electrical energy usage. Households and businesses require high amounts of energy simultaneously at certain times of the day.

This results in energy supply companies building power stations to meet this high capacity, while a more even distribution of energy demand would lower plant sizes and fuel loads for electricity generation (Zhu, Ma, & Wang, 2009).

2.5.4 Impregnation of PCMS in Conventional Building Materials

It has been noted that PCM materials have been used as thermal volumes for mechanical and passive building systems. Great progress has been made in the impregnation of PCM microcapsules in concrete, mortar, and plasterboard resulting in increased thermal storage, alleviating temperature swings which results in reduced energy usage and increased thermal comfort. Another strategy for PCM use in buildings is PCM slurries. This strategy mitigates the problems associated with subcooling and segregation as the PCM is contained in capsules floating in a conductive liquid. In 2011 Huang, Eames, McCormack, Griffiths, and Hewitt (2011) conducted a study on the use of such materials, which was carried out in Northern Ireland at the University of Ulster. A heating system was built to harness solar thermal energy in a helical coil, which would function on a passive heat exchange basis. The authors found that their results indicated potential for PCM slurries to be used in a myriad of systems, functioning not only as the thermal storage volume but also as the heat transfer medium. This opens possibilities for its use in heating, cooling, air-conditioning, heat-exchangers, solar energy, and refrigeration (Huang et al., 2011).

2.5.5 PCM Slurries

Considerable ongoing research is taking place to examine the properties of PCM's and refine the chemical composition of both organic and inorganic types to further the development of biphasic materials which can then be used for thermal energy storage and transfer. Huang et al (2005) illustrates the wide variety of PCM slurry types being tested by research institutions and industry. The slurry thermal capacity, thermal conductivity, melting point, viscosity, and rheological properties must suit the system and the purpose. Inaba (2000) describes five types of PCM slurry in development or in commercial use.

1. Ice slurries.

Ice slurries are used as a coolant for air conditioning or for refrigeration. In air conditioning slurry ice is generated at night time using cheaper night time refrigeration. A basic slurry ice system is illustrated in figure 2.7, and the use of ice slurries for refrigeration is demonstrated in figure 2.8.

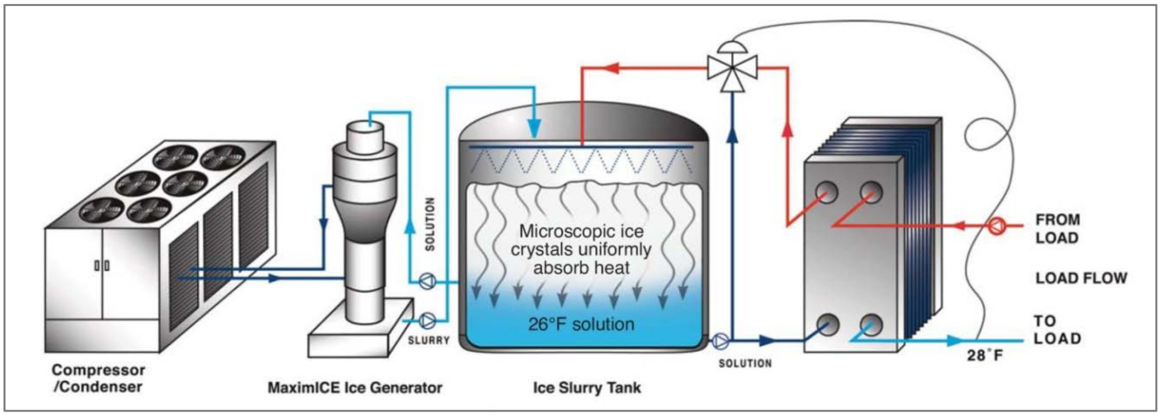


Figure 2.6 Basic slurry ice system schematic (IceSynergy, 2010)

Figure 2.7 Fresh fish chilling using a pumpable deepchill slurry ice system (Goldstein, 2013).

2. Phase change material microemulsions (PCME)

PCME uses a solid to liquid phase change material such as paraffin in water. The paraffin is dispersed through the water in fine particles. The two liquids are immiscible and thermodynamically unstable so an emulsifying agent is added, see figure 2.9, to prevent lumps from forming and the adhesion of the particles to the container walls.

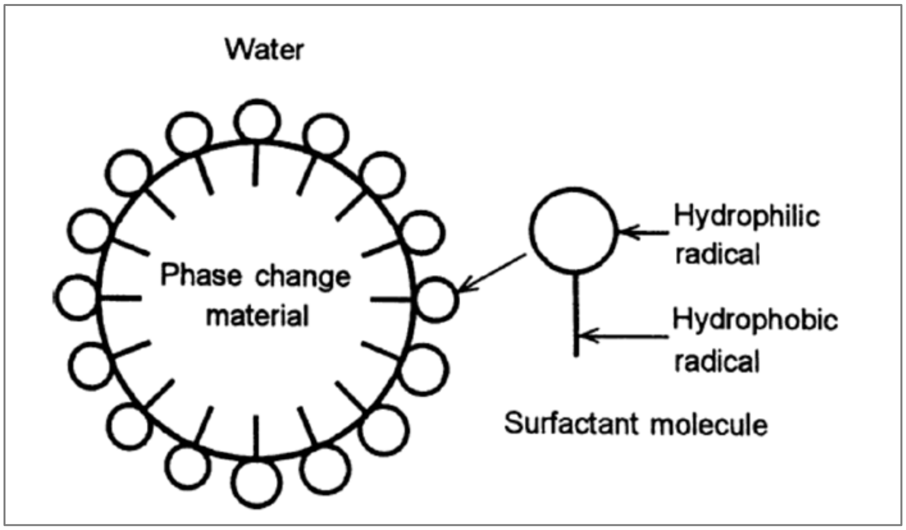


Figure 2.8 Micelle structure around phase change material (Inaba, 2000, p. 999)

3. Microencapsulated PCM slurries (MPCM slurries)

Microencapsulated PCM slurries (MPCM slurries) consist of PCM particles encapsulated in two layers of polymer such as polystyrene, polyamide, and fluoride, as illustrated in figure 2.10. According to Inaba the thermal resistance of these microcapsules is very small, the diameter is between 1-5 µm, and the physical strength is controlled by the outer film thickness which ranges from 2-10 nm, which can be seen in figure 2.11. The coating of the PCM prevents the suspended PCM from accumulating and separating from the water, allowing the fluid to maintain consistency.

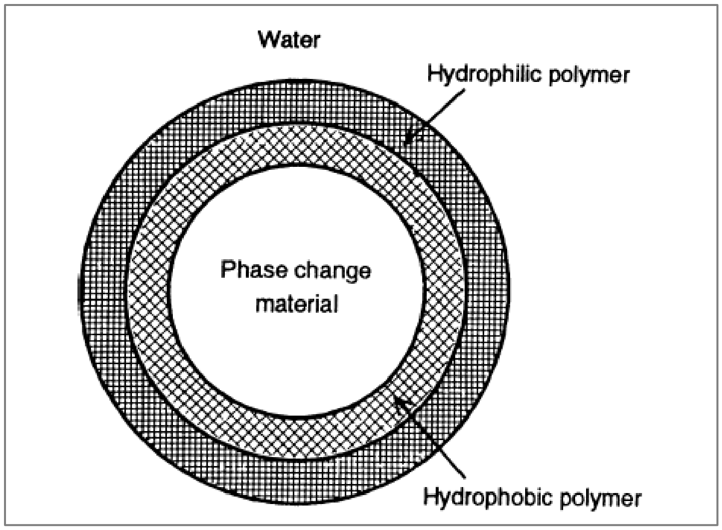


Figure 2.9 Two film layers microcapsule (Inaba, 2000, p. 1001)

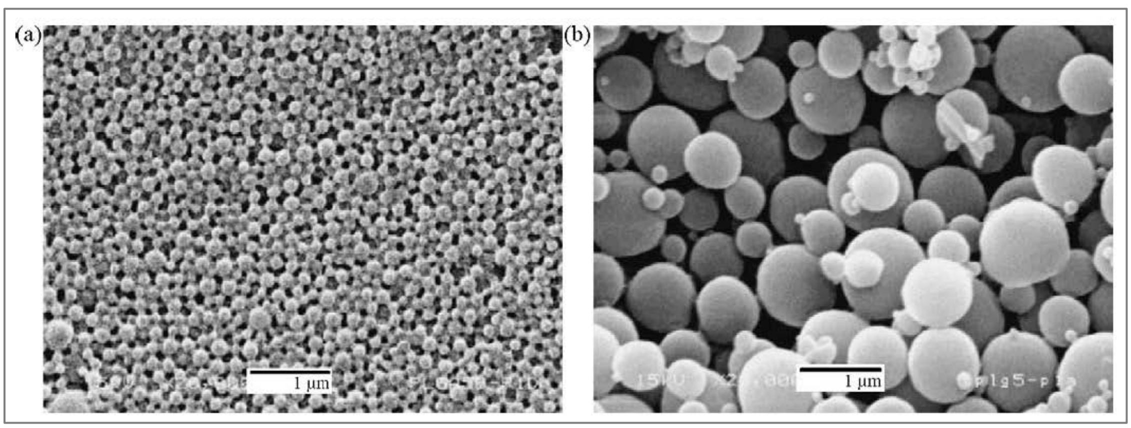


Figure 2.10 Typical appearance of microencapsulated phase change material (MPCM) under a microscope. (Zhang, Ma & Wang, 2010, p. 600)

4. Clathrate hydrate Slurries (CHS)

CHS is an inorganic PCM structure where clathrate hydrate particles contain water molecules that act as a base for other molecules to join. The molecular structure of the study is illustrated in figure 2.12. The formation and separation of the particles stores and releases thermal energy, its typical appearance under a microscope can be figure 2.13.

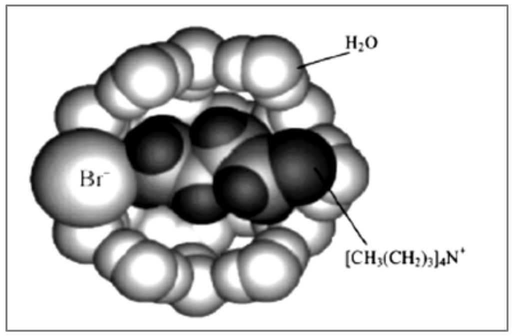


Figure 2.11 Molecular structure of a clathrate hydrate slurry, specifically Tetra-n-butylammonium bromide (Zhang, Ma & Wang, 2010, p. 606)

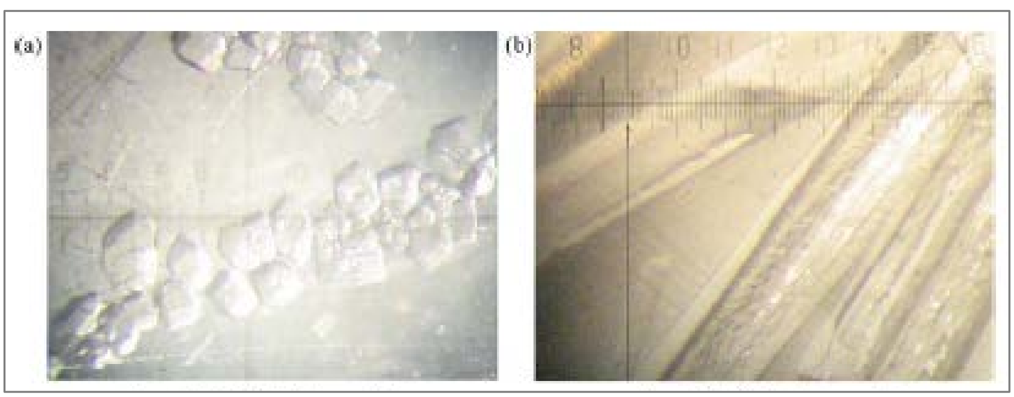


Figure 2.12 Typical appearance of clathrate hydrate slurry under a microscope. (Zhang, Ma & Wang, 2010, p. 607)

5. Shape-stabilized PCM slurries (ssPCM slurries)

SSPCM is a system where PCM is embedded in a support material that has a melting temperature higher than that of the paraffin. The PCM remains stationary and doesn't leak from the high density polyethylene support; a sample can be seen in figure 2.14.

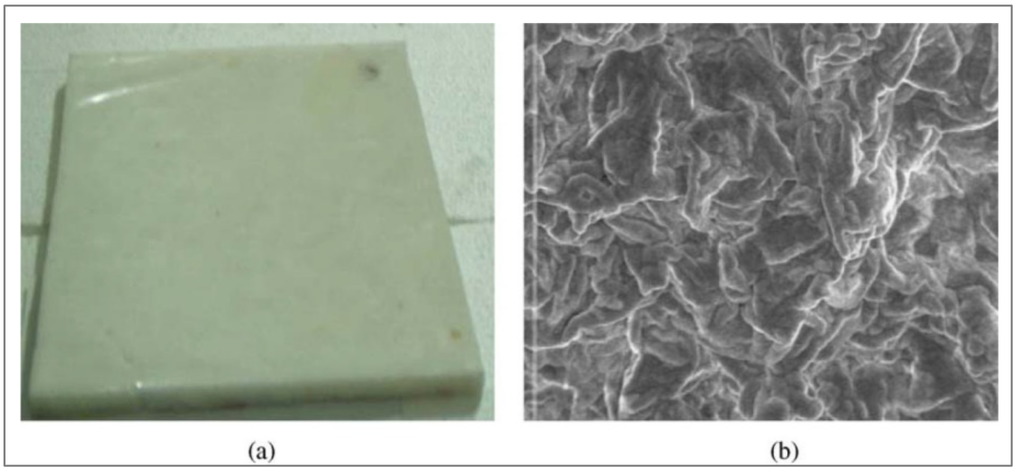


Figure 2.13 Shape-stabilized PCM (a) PCM plate (b) photo of the surface of the plate taken by a scanning electric microscope (SEM) (Zhang et al., 2006, p. 1263)

There has been an increase in the interest and resources being dedicated to PCM slurry research as the potential benefits of such systems are theorized and experimented with. There is still considerable research potential in the area as academics and industry strive to further understand and refine PCM slurries. An overview of the advantages, disadvantages, and applications of the different PCMS is gathered in figure 2.15. The material behaviors are illustrated in figure 2.16, showing the PCM in solid and liquid states.

PCS system	Advantage	Disadvantage	Application
Clathrate slurry	High enthalpy capacity	High dissociation pressure	Air conditioning Solar thermal engineering
Microemulsion slurry	In the presence of a good surfactants: no sedimentation	Time behaviour by alteration of particle size distribution	Air conditioning Solar thermal applications
Shape-stabilized PCM slurry	High heat transfer rate	Possibility of destruction of plastic structures	Air conditioning Hot water supply Solar engineering
Microencapsulated PCM slurries	Large range of melting temperatures High thermal cycling resistance	Destruction of capsules possible Sedimentation Creation of skin layers in open systems	Air conditioning Solar thermal heating Cooling of electronic devices

Figure 2.14 Overview of some phase change material systems (Youssef, Delahaye, Huang, Trinquet, Fournaison, Pollerberg, & Doetsch, 2013, P. 125).

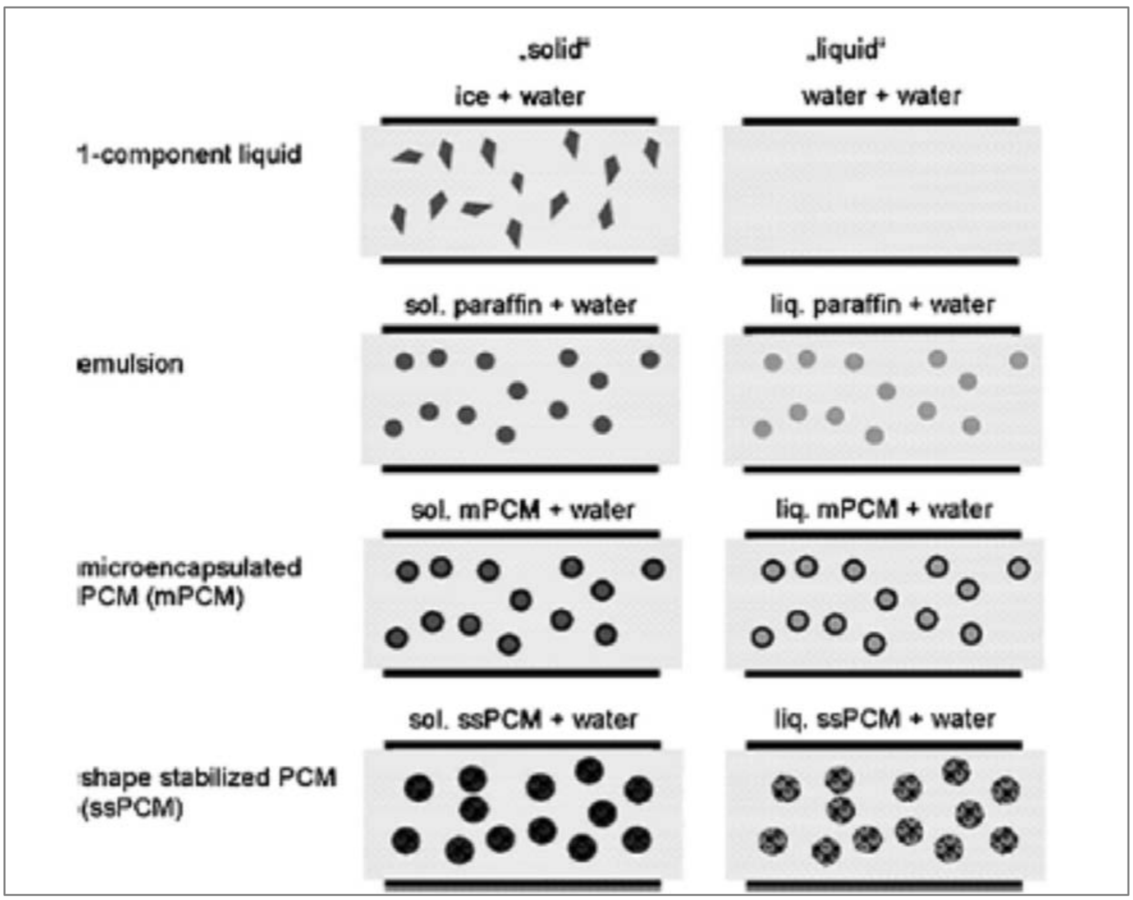


Figure 2.15 Schematic drawing of different types of PCM slurries when in solid state and in liquid state (Delgado, Lazaro, Mazo, & Zalba, 2012, p. 254).

2.5.6 Comparative Analysis of PCM Slurry Systems

Ice slurry and shape-stabilized PCM slurries are currently not considered appropriate for the transfer of thermal energy for heating in historical buildings as ice slurries are used for cooling and the shape-stabilized PCM slurry is not a fluid that can act as a transport medium for thermal energy.

Zhang et al (2010) compared the properties of CHS in comparison with MPCM. It was found that while both materials have substantial thermal storage properties, CHS unlike MPCM is a non neutonian fluid, meaning its fluid movement is not similar to water. CHS also has a high viscosity that can create a problem for heat transfer performance. According to Zhang et al (2010) MPCM is more suited to use in pipes and fluid systems as it has a viscosity and fluid movement similar to water. Delgado et al (2012) building on the research of Zhang et al compared the properties of MPCM's to PCME's. The main problems analyzed in relation to these slurries was subcooling and stability.

During the testing of PCME's it was found that the samples obtained from Aero-University of Ljubljana showed subcooling of about 10oC, indicating that an additional 10oC is required by the sample to initiate the phase change moment and subsequent release of thermal energy. Samples of PCME from Fraunhofer UMSICHT were also removed from the study as they showed substantial stratification without an emulsifying agent and damage to the storage container after two months. A schematic of the possible results of instability of PCME's can be seen in figure 2.17.

The study by Delgado et al (2012) discussed the potential of PCME's but showed that more detailed research needs to be carried out to mitigate the issues of segregation and container corrosion.

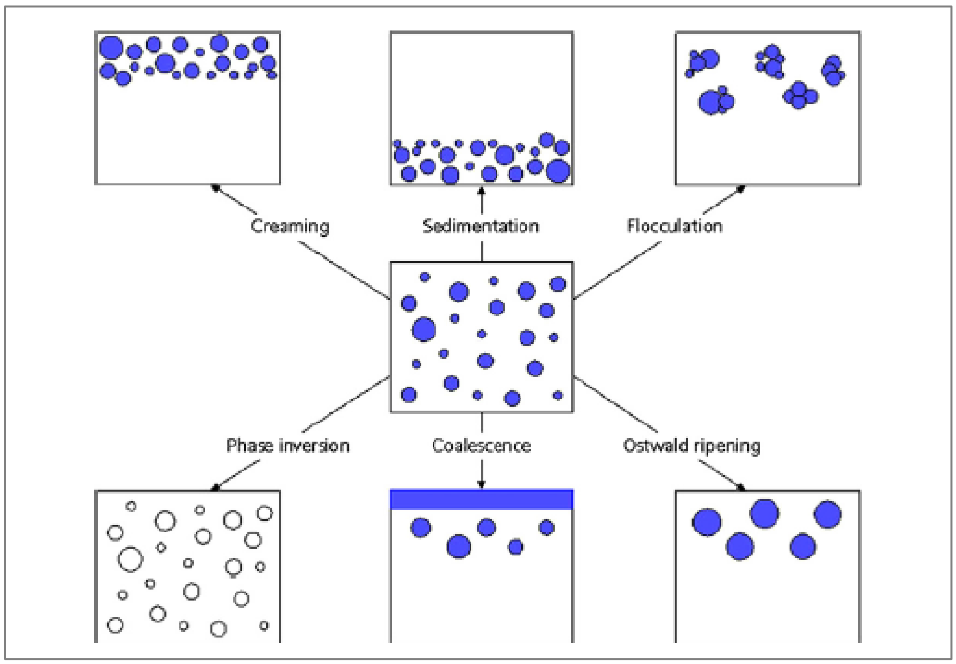


Figure 2.16 Schematic of possible results from instability in a biphasic fluid mix such as PCME (Delgado, Lazaro, Mazo, & Zalba, 2012, p. 262).

In MPCM's the issues of subcooling and stability are mitigated by the use of a polymer on the outside of the paraffin in conjunction with a stabilizing agent in the fluid. The resulting MPCM is stable and homogeneous, which prevents build-up and deposits in thermal systems. One concern of the use of MPCM is the potential for capsules to burst in heat transfer systems, which could lead to deposits of paraffin in bends and pumps. Gschwander, Schossig, and Henning (2005) performed experiments with

MPCM’s made by the chemical company BASF to determine the durability of the material. The experiment involved pumping of MPCM’s at a rate of 800 cycles per day over a number of weeks. It was found that the pump could damage the microcapsules but an increase in shell thickness and a decrease in diameter of the capsule would be effective in preventing this problem. Figure 2.18 shows the damage done to MPCM during the first test and the improvement after modification.

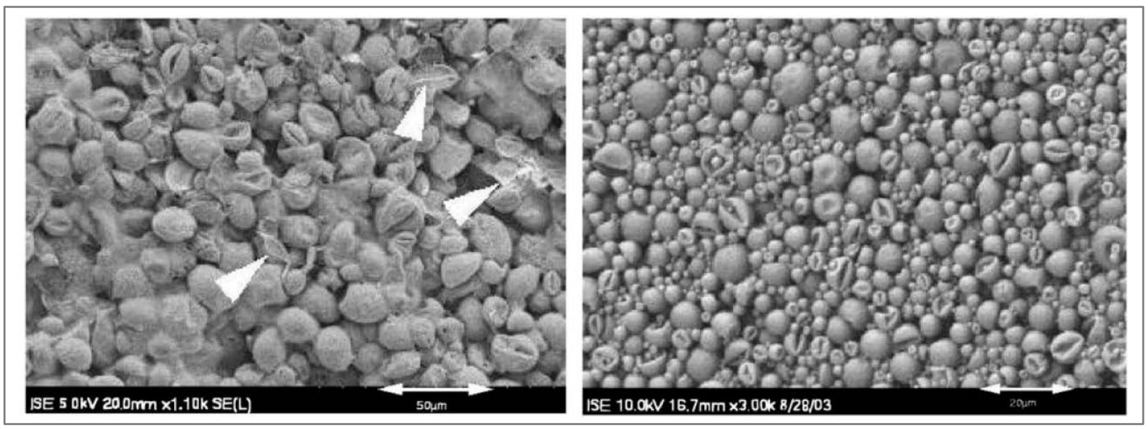


Figure 2.17 Scanning electric microscope (SEM) images of MPCM’s. capsules. MPCM’s to the left show damage as indicated by the arrows, modified capsules to the right remained intact after several weeks of pumping cycles (Gschwander, Schossig, & Henning, 2005, p. 312).

MPCM’s in a liquid medium such as water have been shown to be a stable and effective way to transfer thermal energy in a system (Huang, Eames, McCormack, Griffiths, and Hewitt (2011). MPCM’s are commercially available and are manufactured by chemical companies such as BASF, Microtec, and Rubitherm GmbH.

There has been an increase in the interest and resources being directed towards PCM's as the potential benefits of such materials are theorized and experimented with. There is still considerable research potential in this area to help academia and industry to understand, and further refine these materials.

2.5.7 MPCM Slurry Molarity

In studies by Huang, Eames, McCormack, Griffiths, and Hewitt (2011) and Inaba, Zhang, Horibe, and Haruki (2007) the molarity of the microencapsulated phase change material (MPCM) slurry was shown to be important. A high percentage of Microencapsulated phase change beads was shown to reduce the fluidity of the liquid impacting on the mechanical system's pumping equipment and on its ability to transfer the fluid around the pipe network effectively. Other challenges with high molar concentration include a reduction in the conductivity of the fluid. Too low a concentration would limit the latent storage potential.

Huang et al (2011) conducted a study using MPCM slurry concentrations of 25%, 35% and 50%. The researchers found that the 50% solution was not thermally conductive enough to release energy as it passed through the heating system while the 25% and 35% concentrations showed a temperature decrease between the inlet and outlet points of the system. The results of this study can be seen in figure 2.19.

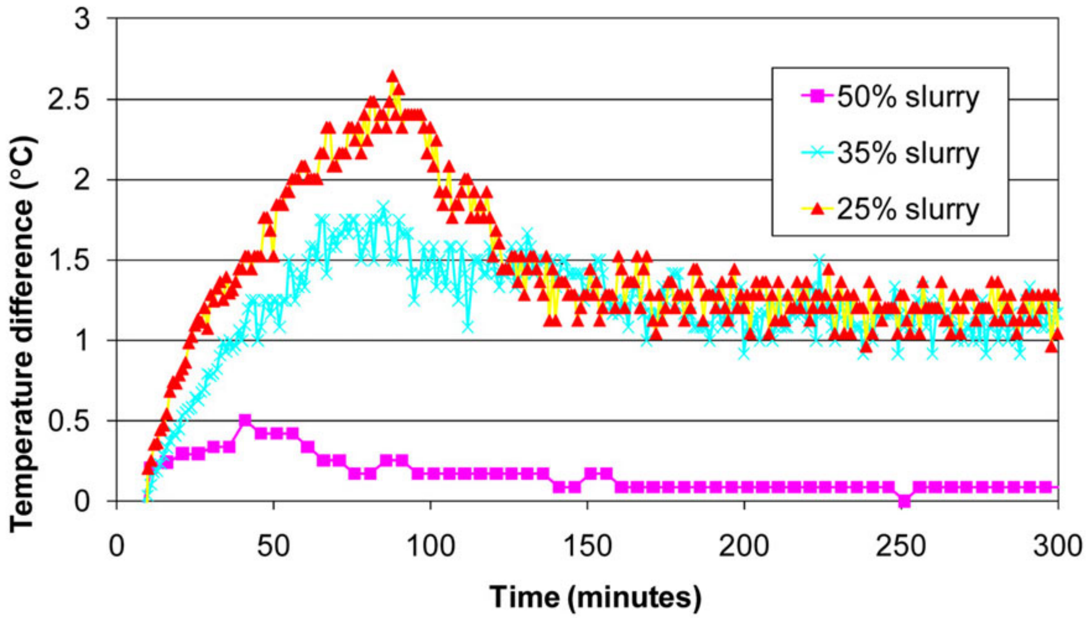


Figure 2.18 Temperature difference between heat exchanger inlet and outlet water temperatures to for three different PCS concentrations with time (Huang et al 2011, p. 2936).

Inaba et al (2007) performed a numerical simulation of the effect of PCM on the convection of heat, the study found that when compared to non phase change liquids the MPCM slurry had a higher heat transfer coefficient. MPCM with a molarity between 20-40% showed a decrease in the convection coefficient as the molarity increased due to increased viscosity, while the MPCM slurry with a molarity between 10-20% showed a decrease in the convection coefficient when the molarity decreased as a result of the reduced influence of the latent heat.

2.6 Summary

There is potential for improvements to be made in the existing building stock with the use of whole building strategies. Governments are changing legislation to reflect growing concerns for the environment and energy supply and security. Historical buildings require a more gentle and sensitive approach in order to protect their character, structure and internal artifacts.

New technologies and analytical software are changing how efficiently we can design new buildings, upgrade existing building stock, and reduce national energy demand. Some of these technologies are not suitable for historical buildings but some such as PCM's may be suitable. The following research aspires to identify ways that PCM materials could be used in conjunction with known restoration methods to improve the thermal efficiency and comfort of threatened historical structures.

CHAPTER 3 FRAMEWORK AND METHODOLOGY

The intention of this methodology is to describe the framework and type of research carried out in the exploration of the research question "Can the central heating system of Sligo Town Hall, Sligo, Ireland, be retrofitted with phase changing material slurry to improve thermal energy performance? What would be the estimated percentage improvement and payback period?"

The research intends to expand existing PCM knowledge and industry understanding of sustainable retrofitting. The construction industry has learned through experience the challenges associated with retrofitting of buildings for energy conservation, such as hygrothermal movement, and subsequent structural and aesthetic damage. Such problems are not acceptable in structures listed as national monuments and alternative solutions must be generated to protect built heritage, improve thermal comfort, and increase energy efficiency.

The research was conducted using a case study methodology. The author used a variety of sources to investigate PCM application in Ireland. The intention of the research was to assess the levels of energy consumption in a historic building, identify challenges associated with the maintenance and upgrading of these structures and assess the potential application of PCM technologies.

3.1 Case study Methodology

In order to investigate the potential of phase change materials in retrofitting historic structures, a case study approach was used. Case study was chosen as the most suitable methodology as it allowed the feasibility of the research question to be examined in a format that can consider a ‘real world’ application in detail and allows for the use of multiple sources. The American Psychological Association describes case studies as follows: “Case studies illustrate a problem; indicate a means for solving a problem; and/or shed light on needed research, clinical applications, or theoretical matters” (The American Psychological Association, 2010, p. 11).

John W. Creswell of the University of Nebraska, Lincoln considers the case study approach to be qualitative where different types of data are collected with the intention of developing an in depth understanding of one or more cases resulting in the generation of a case description. He defines a case study similarly to the American Psychological Association, identifying three main elements: an issue, an exploration of the issue, and context for its study, “case study research involves the study of an issue explored through one or more cases within a bounded system (ie a setting, a context)” (Creswell, 2007, p. 73).

Hancock and Algozzine also describe a case study as qualitative and describes in detail how to plan, conduct and write up a case study, proposing that case studies “can directly influence policy, procedures and future research” (Hancock & Algozzine, 2007, p. 9).

The main characteristics of case studies are also noted and elaborated on by Hancock and Algozzine, they note that the exploration of the issue is very descriptive as it contains varied sources of information, and as it takes place in its own context, the case study is anchored in a specific time and place.

There are a number of different types of case studies, determined by the number of individuals or components in the study. Creswell notes that the intent of the case study defines the type of study and discusses three kinds of research intent.

1. Single instrumental case study

The researcher identifies a problem then chooses a single case to investigate the issue.

2. Multiple or collective case study

The researcher identifies a problem then chooses multiple cases to investigate the problem.

3. Intrinsic case study

The case study is focused on the case study itself. This method is used with a unique issue.

In case study research a procedure for conducting the research is necessary. This provides the framework for the research, laying out legitimate data sources, the sequence of actions required, and the potential conclusion to the study. This prevents the inclusion of unrelated data and the researching of issues which do not further the core issue. Considering Stake’s (1995) approach, Creswell (2007) sets out a procedure for conducting a case study consisting of five steps; 1) initial assessment, 2) Identify case to be studied, 3) data collection, 4) data analysis, and 5) final interpretation.

1. Initial Assessment

An initial assessment must be made by the researcher as to the suitability of the case study methodology for the research project. “A case study is a good approach when the inquirer has clearly identifiable cases with boundaries and seeks to provide an in depth understanding of the cases or a comparison of several cases” (Creswell, 2007, p74).

2. Identify the case to be studied.

The three possible types of case study should be considered along with the research objective.

3. Data Collection

Data is gathered from multiple sources to provide information on pertinent aspects of the case study. Creswell notes that Yin (2003) recommends six data sources: documents, archival records, interviews, direct observations, participant observations, and physical artefacts.

4. Data analysis

According to Creswell data analysis can be ‘holistic’ or ‘embedded’. ‘Holistic analysis’ studies the whole case and ‘embedded analysis’ studies a singular aspect of the case. Presented data may include broad information on the case to provide a background for the issues of particular interest. These specific issues are presented in greater detail but are not designed to be generalised.

5. Final interpretation

The researcher communicates the key pieces of information and results of the study, communicating what has been learnt as a result of the study (Creswell, 2007). “Reporting focuses on describing the case with description, analysis, and interpretation addressed differently or equally. Decision is made to emphasise objective or subjective reporting, including biases and generalisations to other cases” (Hancock & Algozzine, 2007, p24).

Hancock and Algozzine (2007) advise the addition of an supplementary step; confirmation of the case study findings. Confirmation strategies such as sharing the results with participants, other case study researchers, and experts in the area of study. Triangulating the data with good sources provides validity and reinforces the quality of the research results and conclusions.

There are challenges associated with the case study methodology. The researcher must identify the case or cases and the choice is subject to the researcher’s judgement. The rationale for the choice must be represented. There is a need with case studies for boundaries to be set, not all case studies have defined beginnings and endings, the researcher must define the extent of the study. Interpretation is also performed by the researcher meaning that bias, cultural perspective, and the extent of the researchers understanding of the related issues can influence the results and conclusions.

The preparation of a case study approach can be informed by previous similar studies which have already been carried out. In a study by Sunikka-Blank, Chen, Britmell, and Dantsiou (2012) titled 'Improving Energy Efficiency of Social Housing Areas: A Case Study of a Retrofit Achieving an "A" Energy', a singular dwelling was used as the basis for a case study. The researcher's identified the issue, that of the households being 'fuel poor' which means that more than 10% of the household income is spent on fuel and energy. The specific house was located in a social housing area in Trumpinton, Cambridge, England. The social housing scheme is partly owned by Cambridge City Council and was built in the 1950's. A strategy for the retrofit and data collection was established with reference to the context and method for sustainable retrofitting and government legislation. It was acknowledged that the design would be broadly generalizable to the approximately 37,500 similar social houses that form part of the UK's social housing stock (Sunikka-Blank et al., 2012).

The retrofitted building was monitored throughout construction, for energy use and suitability of modifications. The occupant behaviour was also monitored and recorded. The case study was applied to one typical social housing dwelling in a 'real world' situation with the intention of informing further research and policy creation.

3.2 Case Study Initial Assessment

Following the Creswell (2007) case study methodology a problem was identified, that of the challenge of upgrading the thermal energy performance in buildings which are historic. These buildings may be nationally protected structures due to historical significance, building type, or to help retain the character of an area.

Phase change materials were identified as a possible method to improve thermal performance without damaging the buildings aesthetics or structure. The use of phase changing materials (PCM's) in buildings is a new area of technological development in the construction industry. The applications of such materials has been speculated for new build construction and the validity of these theories is still being tested in lab based quantitative studies and test builds. This research aspires to enhance this body of knowledge and test the use of PCM's in historic structures.

The research intention was to investigate the possibility of retrofitting the central heating system of an existing historical building with microencapsulated phase change materials in order to improve its thermal performance. The addition of MPCM would theoretically extend the heating of the room once the heating is switched off, as the MPCM would release a burst of heat at a specific temperature as the radiators cooled. Originally the researcher had considered replacing the water in the closed loop radiator system with MPCM Slurry (MPCM and water), however, following careful consideration an alternative experiment attaching the MPCM to the outside of the radiators was performed.

3.3 Consultation

Insight into the sensitive retrofitting of historic buildings and the use of MPCM slurry was gathered from communication with experts and academics from the realm of sustainable architecture, materials engineering, and sustainable energy use. Problems associated with neglect and improper retrofit of historical buildings, field experiment design, PCM choice, and external validity were discussed.

3.4 Sligo Town Hall

The chosen natural setting for this study was Sligo Town hall designed by William Hague and built circa 1865. This building was chosen based on the researcher's geographic location, the temperate climate of the region, and the researcher's prior employment in the building. The researcher had a summer internship in the architects department in 2005.

Sligo Town Hall, shown in figure 3.1, provided a suitable structure due to the presence of key characteristics, primarily due to its age and construction type. It has a traditional solid stone wall construction with timber flooring, and a timber and slate roofing structure. The building has large volumes and was designed for passive ventilation and convective heating. Sligo Town Hall is managed by the government and is subject to energy conservation legislation, has regular scheduled opening hours, and is a protected structure both internally and externally, meaning that it cannot be significantly altered outside or inside.

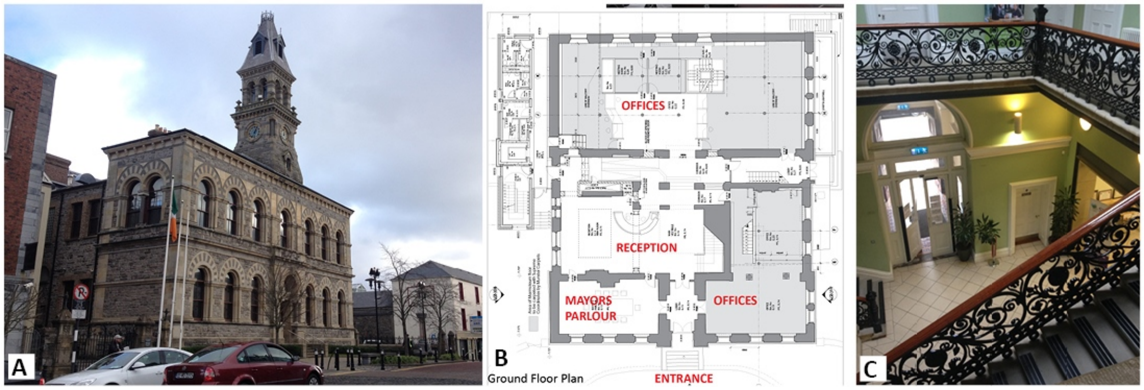


Figure 3.1 Sligo Town hall survey details showing (a) the exterior facade (b) the ground floor plan, and (c) the entrance and reception from first floor level

Following a number of site visits and a guided tour by the building porter, observations and information on the characteristics of the heating system and the relationship of the occupants with the building were gathered. Detailed observations were confined to the foyer, Mayors Parlour, canteen, and boiler room. The foyer and Mayors Parlour can be seen in figure 3.2.

Figure 3.2 Sligo Town hall photographs showing (a) the reception area, and (b) the Mayors Parlour

The building was renovated circa 2000 in order to improve its appearance and its thermal properties. An additional layer of glazing was added to the interior of the original single glazed windows. New period style radiators with thermostats were added and underground heating was installed in the foyer and Mayors Parlour, which is shown in figure 3.3. Observed and reported areas of thermal inefficiencies included the location of non-traditional panel radiators behind timber panels for aesthetic purposes, the panels can be seen in figure 3.4 part A. This arrangement interferes with the radiators ability to effectively heat air by convection. An aluminium mesh replacement for the timber panel was planned and granted planning permission but never implemented due to economic concerns.

The Mayors Parlour has an open gas fireplace, see figure 3.4 part B, which is used to provide a heating boost prior to and during meetings, it is switched on before meetings but only switched off when the porter closes the building at the end of the day.

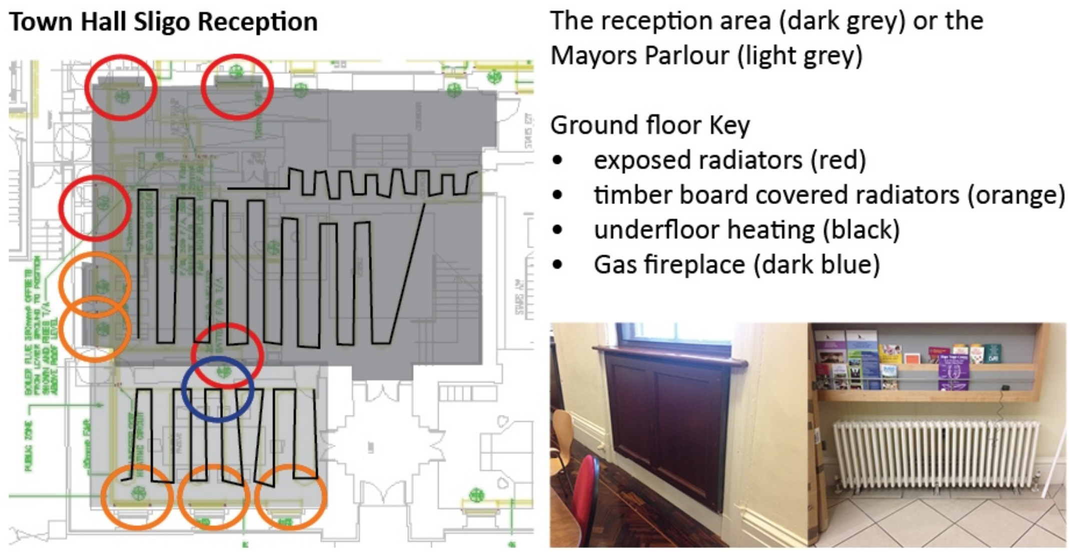


Figure 3.3 Sligo Town hall survey details showing the location of radiators and underfloor heating

Figure 3.4 Sligo Town hall survey details showing (a) radiators behind timber panels, and (b) open fireplace located in the Mayors Parlour

The building heating switches off at 4.30pm, thirty minutes before closing at 5pm. Some staff working at this time use portable electric heaters at this time of the day to increase the air temperature in their office. The use of electric space heaters is not considered an efficient or cost effective measure to manage heating in an old building. Electricity is a very high grade of energy and it is both expensive and inefficient to use it to create a lower grade of energy as energy is lost in each state conversion (Boyle, 2012) According to Sustainable Energy Authority of Ireland (SEAI) the efficiency of the Irish electrical supply including renewable energy was 48% in 2013 (SEAI, 2015).

Radiators are fitted with thermostatic valves which were reported to break easily as occupants attempt to augment their environment. These items are expensive to repair and are not considered a priority by council maintenance and repair staff. Functioning thermostats are set to the highest temperature setting in spite of overheating in smaller rooms as staff report the building cools rapidly once heating is turned off. Figure 3.5 shows an a portable electric heater and a broken thermostatic valve located in the foyer of the Sligo Town Hall.

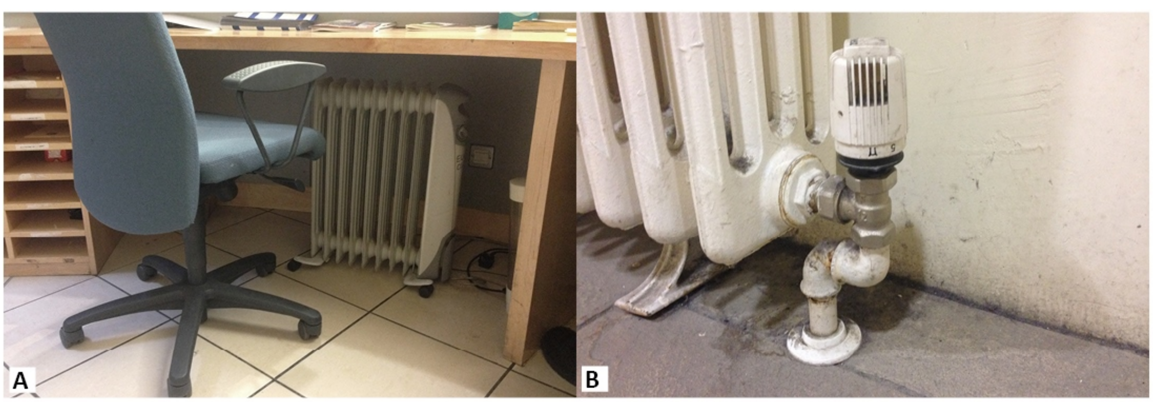


Figure 3.5 Sligo Town hall survey details showing (a) portable electric radiator in use, and (b) traditional radiator style with thermostat

The building has a SYGMA Automated Building Management System. This computer based system can be remotely programmed to regulate and monitor the flow temperature, schedule of operation, and fuel consumption. The heating system at Sligo Town Hall is zoned, the pipes have been updated and insulated where accessible and the boiler is inspected annually.

The SYGMA system was installed to manage occupant comfort and conserve energy but there have been some issues with its operation in the last 3 years. The SYGMA Building Management System is not currently remotely accessible, according to SYGMA, the network cable has most likely been disconnected from the network and the local authorities IT staff should be asked to reconnect it. Unfortunately, the location of network cable is unknown, the last facilities manager to have access to the system has changed position and has not been replaced. The boiler control thermostat is set at 83°C (180°F) and the central heating is scheduled to turn on at 08.00am and turn off at 16.30pm every week day, running for a total of 8.5hrs per day. SYGMA need to return to maintain the system and but financial constraints prevent this as it is considered not income generating spending. IT staff are understaffed and lack technical support for main services, the absence of an official facilities manager means that this problem will not be resolved in the short term.

The SYGMA control panel for Sligo County Council Riverside offices can be seen in figure 3.6. This building's system control is the same as the inaccessible Sligo Town Hall controls. Riverside is made up of a building from 1870's with a 1960's extension; it has the same business hours as Sligo Town Hall. The system operates from 7.30am to

4.30pm and switches off at intervals throughout the day. In total it runs for 7hrs in a 9hr heating period.

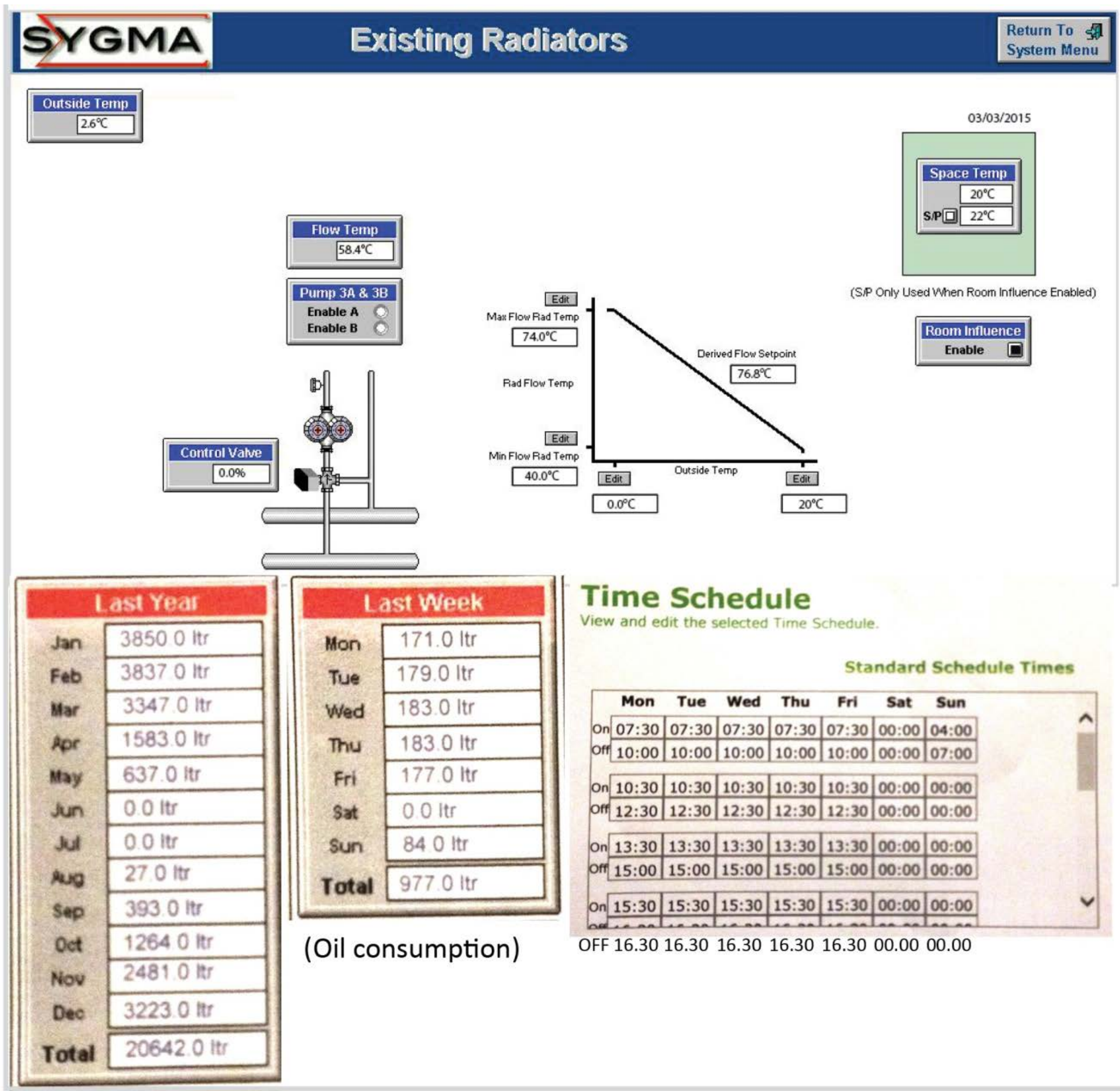


Figure 3.6 SYGMA automated building management system data for The Riverside Offices, Sligo. In this building the system controls are accessible and it has the same business hours as Sligo Town Hall. The flow temperature, oil consumption, and time schedule are shown

The surface temperature of an exposed radiator located in the foyer of Sligo Town Hall was monitored from 15:30 on the evening of Friday 6th to 13.45 on Monday 9th of February, 2015 to assess the range of surface temperatures that could occur on a radiator with a boiler thermostat set at 180°F (83°C). A maximum minimum thermometer was used and it recorded a maximum temperature of 56.2°C and a minimum of 8.9°C. The surface temperature of a radiator in any system can vary depending on the distance from the boiler and possible presence of air pockets or limescale built up in the radiator. The temperature of the radiator was visually recorded at intervals and the results can be found in table 3.1.

Table 3.1

Visually Recorded Radiator Surface Temperatures, and Maximum and Minimum Temperatures for the Data Collection Period in the Foyer of Sligo Town Hall

Time	Temperature
Friday	
3.30	33.9°C
4.15	30.6°C
4.45	25.9°C
6.00	22.4°C
6.30	21.4°C
7.00	20.8°C
Monday	
8.00	48.8°C
8.25	52.8°C
9.00	54.0°C
9.25	50.9°C
10.45	51.0°C
13.45	50.0°C
Maximum recorded temperature	56.2°C
Minimum recorded temperature	8.9°C

3.5 Case to be Studied

The exploration of the challenges associated with the heating of historical buildings was guided by the study of Sligo Town Hall. A renovation completed circa 2000 utilised recommended strategies of draft proofing, insulating, and upgrading of boiler equipment to sensitively retrofit the historic structure, seen in figure 3.7. Although largely successful the financial constraints on repairs, lack of access to heating system controls, and the use of electric portable heaters by staff is not economically ideal or energy efficient. This research proposes a latent heat approach to improving the thermal performance of the building. It was reasoned that a small, single room study be carried out to determine if MPCM's can improve the thermal energy performance of such a building, the results of which could then be inferred up to a whole building.

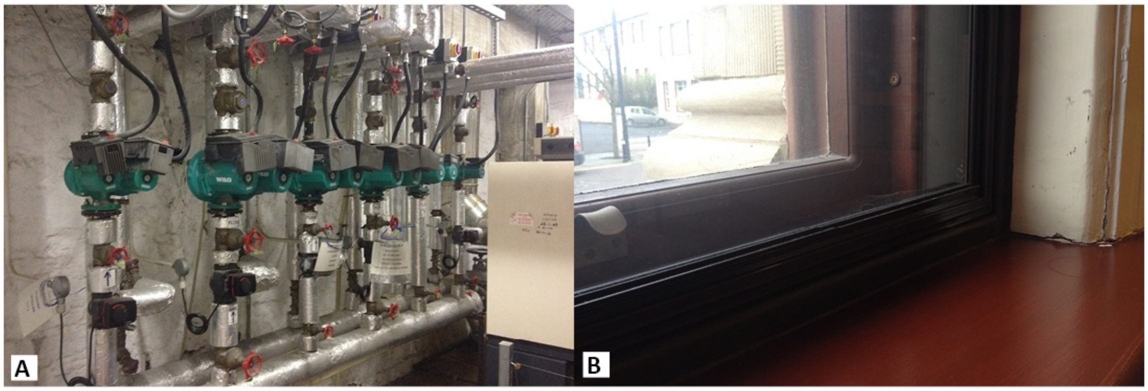


Figure 3.7 Sligo Town hall survey details showing (a) zoned and insulated heating pipes, and (b) additional glazing layer

Sligo Town Hall is occupied by local authority offices not generally accessible to the public. The occupancy and user influence on the space such as adjustment to thermostatic valves, and opening of windows and doors could not be controlled. The building is also closed in the evening and at weekends making accessibility to data collection restricted. It was decided that a room in an alternative building should be used as a substitute test space. The room would need to have a similar construction to that of Sligo Town Hall, and be accessible and controllable by the researcher. A domestic house at Rossinver, Co. Leitrim, Ireland was chosen.

Gathering pertinent numerical data for the case study analysis was done in three ways. Firstly, the design and energy use data was collected for the existing building, secondly an experiment was run to evaluate four different heating systems within the test space, and thirdly, a comparative analysis between the four systems was carried out to assess the possible change in thermal energy performance when applied to an office typology occupant profile such as is the case in Sligo Town Hall. The four heating systems included; no heating, heating with radiator only, heating with a MPCM slurry thermal store and radiator, and finally heating with a water thermal store and radiator. The order of the test can be seen in table 3.2.

Table 3.2

Test Week Period and Applicable Intervention

Period	Intervention
Week 1	No radiator
Week 2	Radiator only
Week 3	Radiator with 20 litres of MPCM slurry
Week 4	Radiator with 20 litres of water

Analysing the impact of MPCM based and non MPCM based heating systems on the substitute building was intended to provide credible data to support the researcher’s exploration of the research question. The research analysis will contribute to the development of strategies for sustainable retrofitting and provide assistance for future applied quantitative studies.

3.6 Test Room at Rossinver, Co Leitrim

The test building needed to fit certain requirements in order to be a suitable location to perform the experiment. It was required that the room be accessible outside of working hours and could be controlled both for heating and occupancy. The chosen building was a domestic building owned and occupied by Mr. Edmund Connolly, a retired electrician. The building has two stories and has a building footprint of $68m^2$. The ground floor contains a kitchen living area, hallway, bathroom, and sitting room. The upper level contains four bedrooms and one wash closet (WC).

The building walls are solid stone and the roof structure is constructed of timber rafters, a waterproof membrane, timber battens and natural slate. The building was originally a shop with living space upstairs and is approximately 200 years old, it first appears on Ordinance Survey Maps in 1829 when the first large scale survey of the entire country was conducted. It is not a protected or listed structure. Originally the building was lime washed, it is now plastered and painted with a stone facing on the front face to first floor level.

The building is heated using a home heating oil burning stove, the radiators are gravity fed and are controlled by the stove operation, when the stove is on the radiators are heated continuously for that time period. The stove is not on a timer or any kind of scheduling device, the heating oil must be lit by a match when required. The owner will leave the stove burning twenty-four hours a day at a low heat, considerably warming the room it is in, the two bedrooms directly above it, and continuously supplying the radiators with heat. The location of the test building, exterior façade, and kitchen stove are shown in figure 3.8.

Figure 3.8 Test building at Rossinver survey showing (a) the location in Ireland (b) the building exterior, and (c) the oil fired stove located in kitchen

3.7 Choice of Test Room

It had been proposed to run the experiment in two rooms (test rooms A and B), however the substantial rising heat, presence of a water cistern, and roof insulation in Test Room A would have greatly influenced the room temperature difference between Test Room A and B.

The decision to choose Test Room B was informed by issues including continuous occupancy, security, insulation, glazing, influence from heating sources and control. The room needed to be empty in order to reduce latent heat gains from people and equipment, Room C is continuously used for sleeping with Test Rooms A, B and D used by visitors of varying frequency. The owner lives alone so it was preferable to not create any apparent breaches in the building security, the experiment would require a thermometer to sit outside the window which would make this window more vulnerable to forced entry.

The attic space over the northern side of the building has been insulated with mineral wool, while the southern half is uninsulated. On the west side of the building, original timber framed, single glazed windows have been replaced with PVC framed, double glazed windows which would not be allowed in a protected historical structure. The test room needed to have minimal influence from the spaces around it, and the rooms directly above the kitchen receive large amounts of rising heat from the stove located in the kitchen. The house is regularly visited by family members including families with children, it was preferred that a room of smaller size would be used due to the four week minimum duration of the experiment. The room characteristics and use profiles considered are summarized in table 3.3 and the upper floor plan of the test building, with chosen test room is illustrated in figure 3.9.

Table 3.3

Use Profile and Characteristics of Possible Test Rooms

Name	Size	Use	Security concerns	Insulation above	Original glazing	Influence	Control
Room A	$7.17m^2$	Weekends	No	Yes	Yes	Yes	No
Room B	$6.53m^2$	Weekends	No	No	Yes	No	No
Room C	$10.69m^2$	Continuous	Yes	Yes	No	Yes	No
Room D	$12.38m^2$	Bi-monthly	Yes	No	No	No	No

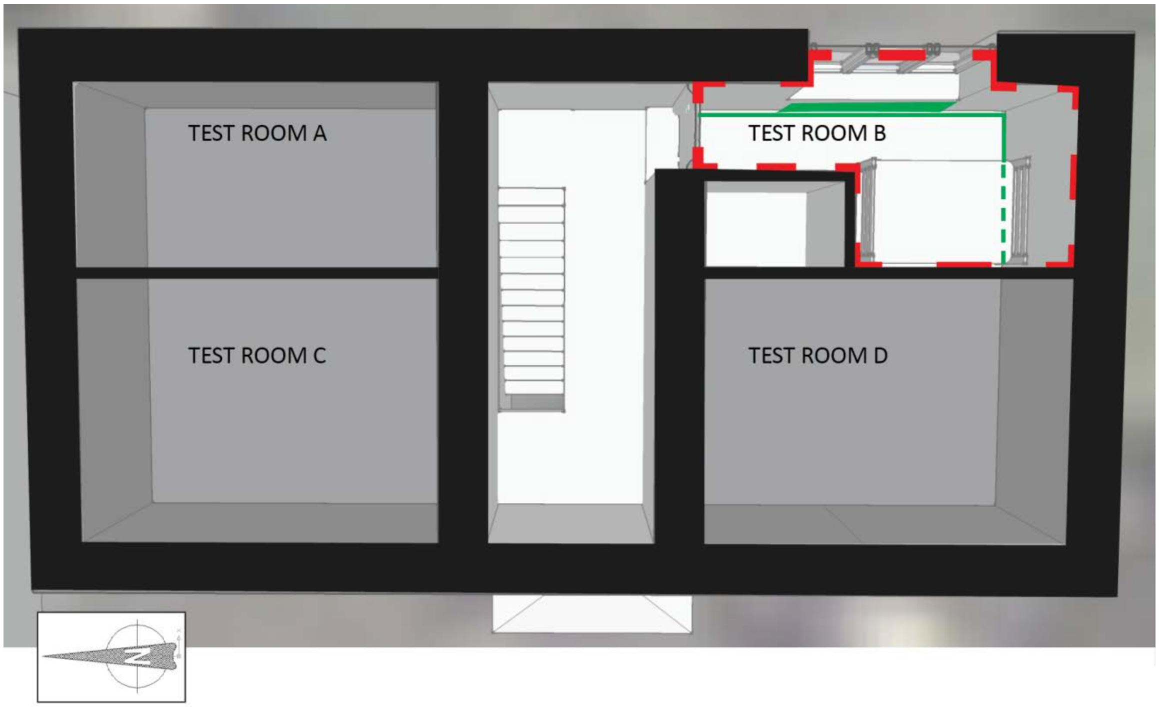


Figure 3.9 Second floor plan of test building at Rossinver, the chosen Test Room B is highlighted

3.8 Data Collection

The collection of reliable data was required in order to fully discuss the research question; can the central heating system of Sligo Town Hall, Sligo, Ireland, be retrofitted with phase changing material slurry to improve thermal energy performance? What would be the estimated percentage improvement and payback period? A case study approach was chosen for the overall analysis while an experimental design was chosen for a part of the quantitative data collection. A case study approach was chosen over a purely quantitative or qualitative research design due to its ‘real world’ relatability. The application of a case study approach in the emerging field of MPCM slurry could potentially lead to further case study analysis and more detailed quantitative studies, as observations are recorded and further understanding is required.

A previous experimental design proposed a lab test box experiment which would analyse the heating and cooling behaviours for MPCM slurry samples of different molarities. Challenges to accuracy and generalisability to a larger volume in a stone building led to a field experiment being chosen instead.

3.9 Experiment Design Methodology

Creswell (2009) and Sekaran and Bougie (2009) discuss experiments as a method to examine if there is a cause and effect relationship between variables, investigating if the independent variable causes the dependent variable.

According to Sekaran and Bougie (2009) there are four conditions that must be met in order to establish that the independent variable has an effect on the dependent variable.

1. The independent and the dependant variable should covary.
2. The independent variable (the presumed causal factor) should precede the dependant variable.
3. No other factor should be a possible cause for the change in the dependant variable.
4. A logical explanation (a theory) is needed about why the independent variable affects the dependant variable. (Sekaran & Bougie, 2009, p227)

The manipulation of an independent variable is called the treatment, this helps establish the degree of influence that the independent variable has on the dependant variable, such influence results are known as treatment effects (Sekaran & Bougie, 2009).

Sekaran and Bougie (2009) illustrate that the validity of the experiment is important, and is discussed in terms of high internal and external validity. High internal validity indicates that the results are more precise but that the findings are not generalizable to other situations; a lab experiment normally has high internal validity and lower external validity. A high external validity indicates that the results are quite generalizable to other situations, field experiments are classified as having high external validity. Nickerson (2005) notes that with high external validity, control over the execution of the experiment can be reduced and unexpected problems can come to light. These problems can cause additional expense and may take considerable time and labor to mitigate. The author also argues that “scalable experimental designs preserving statistical efficiency can free up resources needed to address problems in execution” (Nickerson, 2005, p. 233)

The validity of the experiment is ensured through the control of nuisance variables or contaminating factors and threats to validity. Creswell (2009) lists the ten main threats to internal validity as; history, maturation, regression, selection, mortality, diffusion of treatment, compensatory demoralization, compensatory rivalry, testing and instrumentation. The author also identifies the three main threats to external validity as interaction of selection, setting, and history on treatment. Sekaran and Bougie (2009) list seven threats to internal validity and two threats to external validity. The applicable threats depend on the test method and an awareness and identification of any such threats can help protect the credibility of the data collection.

3.10 Experiment Design Overview

The proposal of the field experiment run at the test building in Rossinver was to collect quantitative data which would support the exploration of the thesis research.

In order to test the hypothesis using a field experiment the independent and dependant variables needed to be known. As the researcher wanted to document the effect of an augmented heating system on the temperature of the room, the heating system was identified as the independent variable and the room temperature was identified as the dependant variable.

The heating system was subjected to four treatments in order to record any cause and effect data. The sensor monitoring the room temperature was placed centrally in the room at a specific location and not moved for the duration of the experiment. The radiator was scheduled to come on at specific times each test day, and timed data collection ensured a data log of equal size and duration for each day. An alternative method for data collection would be to thermostatically set the room temperature and monitor the frequency of times the heating switched on. This method was not chosen as thermostatic controls are not common in historical buildings and occupants often work and live in rooms below what is considered an optimum design temperature for that space. The action of thermostatic control was however mimicked during analysis of the collected data to provide a basis for comparison, and to acknowledge over the indefinite life span of the building, its function may change, and buildings such as, art galleries, museums, domestic houses, residential homes, and medical buildings which require a constant temperature during the day and night. Ideally a historic building would be maintained at a certain temperature to maximise its thermal mass, and protect its structure and internal artefacts.

The four treatments applied to the room were 1) no radiator, 2) radiator only, 3) MPCM slurry and radiator, and 4) water and radiator. The radiator temperature setting remained constant throughout and the quantity of MPCM slurry and water tested were the same. A schematic for the arrangement of test fluids and thermostats is illustrated in figure 3.10.

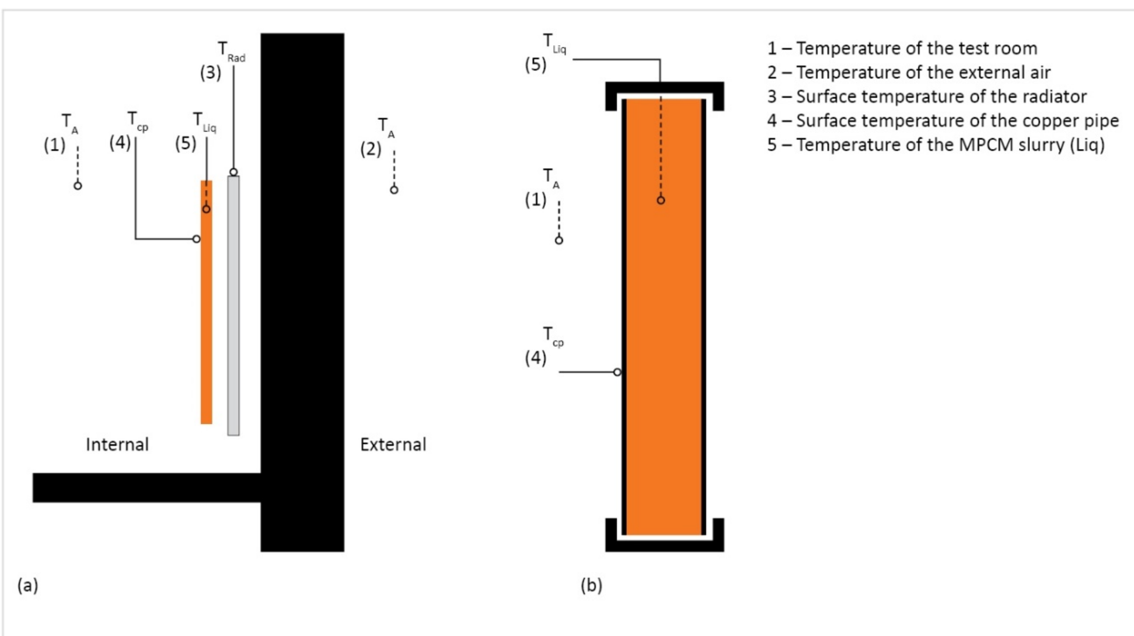


Figure 3.10 Proposed relationship of test fluid containers to thermometers and radiator

The test room was chosen due to its location, neither the room below or adjacent were subject to substantial heating during the test period, preventing undocumented heat gains in the test room. Contaminating factors were controlled where possible to reduce the possibility of a variable not being studied influencing the dependant variable.

Access to the room was also prohibited during the experiment and no non-test electrical equipment was operating in the room. This prevented latent heat being a contaminating factor.

3.11 Energy Calculation

The test building was surveyed, and data on room volume, function, orientation, materials, and temperature requirement was gathered in order to run a comparative analysis between the four systems with reference to thermal energy performance. Calculations on heat loss were prepared, so that the results would then be analysed in relation to energy use, cost, and thermal comfort.

3.12 Choice of Phase Change Material

The information on a number of different PCM based products was gathered and compared to evaluate the most appropriate application in this situation. The material's specific heat capacity, core material, size, volume, molarity, and melting point was dependant on the experimental equipment, cost, and chosen heating profile for the test room. The sampling of data on the MPCM slurry was conducted to provide a solid basis for theoretical hypotheses development and identification of anomalies.

3.13 Data Analysis and Interpretation

Analysis for the data was descriptive, based on the literature, quantitative PCM studies and surveyed building data. This analysis was informed by the literature review discussion of retrofit strategies for improving thermal performance, the risks of such strategies to historical structures, and the relationship of occupants with the buildings thermal environment.

The field experiment compared the test building without heating, with heating, and with two augmented heating systems, essentially comparing the traditional central heating system versus a central heating system with thermal energy storage. Statistical analysis was run using SPSS software, a graphical java based statistical analysis software package from IBM, to determine the descriptives of the logged data.

The numerical data was graphed and visually assessed for differences in the wave amplitude which indicates the temperature swing between heating and non heating periods. Changes were then described in relation to the recommended air temperature for an office environment with particular reference to thermal comfort, heating scheduling, energy and overheating.

The strengths and weaknesses of the data were discussed along with their possible influence on the research. This was necessary to ensure internal validity throughout and to avoid valuable secondary observations being missed.

3.14 Researcher Bias on Sustainable Retrofitting

The researcher has a background in architecture and is of the opinion that historical buildings should be protected not only for historical record but also for their continuing contribution to collective memory and place-making. The identity of urban spaces should be, in my opinion, a built timeline of the city. I am also a strong believer in energy conservation and I support actions that aspire to slow the on-going damage to our environment.

My experience in architecture and the construction industry has led me to believe that there is need for increased research in this area as industry struggles to meet ever increasing energy standards on reduced budgets. Solutions need to be innovative, and generated to work with our natural and built environment rather than against them.

Although the potential contributions of the technology discussed in this research will not substantially influence the energy crisis, it may contribute to making our existing building stock 'less bad'. Historic buildings will be used for hundreds of years to come, reducing their energy requirements could, in the long run, add up to substantial savings for society and the environment.

The researcher may be biased towards the application of microencapsulated phase change material as a thermal energy store for existing heating systems. Challenges with the use of such materials may be inadvertently downplayed.

3.15 Summary

This chapter surmises the methodology and framework utilized for the researcher's data collection and analysis. The researcher bias, location of study, and consultation were discussed to clarify the elements examined by this study. The process for data collection and analysis was also illustrated to show the tools used by the researcher in examining and interpreting the data.

CHAPTER 4. FRAMEWORK DEVELOPMENT

The purpose of this chapter on framework development is to further analyze the chosen case study and illustrate the measures taken by the researcher to develop the practical framework for the execution of the experiment, highlighting steps taken to develop the experimental equipment and parameters, examining challenges that arose during data collection.

Mathematical analysis was completed to determine the critical u-values and the heat losses from the building, the convective heat transfer rate of the radiator, and the thermal capacity for a one degree change in each of the test fluids. This data would support the overall case study analysis, furthering the process of critiquing the data with reference to the thesis hypothesis.

4.1 Building Heat Loss and Electrical Energy Costing

In order to assess the energy profile of the test room at Rossinver, the u-values and watts lost by the building at different temperatures were calculated. The u-values of each building material in each surface were calculated and can be found in Appendix A. These u-values were then used to calculate the rate of heat loss in watts from all the surfaces at 10°C, the mean annual temperature, and 5.3°C, the mean temperature for the coldest month (December), these temperatures are shown in table 4.1 (Met Éireann, 2015). The ventilation heat loss rates at these temperatures were also calculated and added to the surface heat loss resulting in the total heat loss for the test room.

The heat loss through the building fabric was 484.57 watts at an internal temperature of 21°C and an external temperature of 10°C, shown in table 4.2, and the heat loss was 681 watts at an internal temperature of 21°C and an external temperature of 5.3°C. Further calculations were performed for an external temperature of 10°C using internal temperatures of 19°C, 20°C, and 22°C, which can be found in Appendix B.

Table 4.1

Mean Temperature in Degrees Celsius for Finner Automated Weather Station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2015	5.3	4.8	6.2	8.4	9.5	12.3	14.1						8.4
2014	5.6	5.8	7.1	10.3	11.5	14.1	15.8	13.9	13.9	11.1	7.9	6.5	10.3
2013	5.5	5.2	3.7	7.1	9.8	13.6	17.4	15.3	13.8	11.8	7.2	7.5	9.9
2012	6.6	7.7	8.9	7.1	11.4	12.5	13.7	15.8	12.6	8.7	6.6	5.7	9.8
mean	5.3	5.4	6.9	8.5	11.1	13.5	15.3	15.0	13.3	10.4	7.6	5.6	9.8

Note. Weather data based on table by Met Éireann, (2015)

Table 4.2

Heat Loss through Building Fabric at an Internal Temperature of 21^{o}C, with an External Temperature of 10^{o}C, the Mean Annual Temperature

Surface	Area m^2	Inside Temp ^{o}C	Outside Temp ^{o}C	ΔT ^{o}C	U-value	Loss in Watts
Roof	6.5268	21	10	11	1.123	80.62[a]
Floor	6.5268	21	21	0	0.827	5.4[a]
External wall (East)	8.63	21	10	11	1.7556	166.66[a]
External wall (South)	4.56	21	10	11	1.7556	88.06[a]
Internal wall 1	6.504	21	21	0	1.83486	11.9[a]
Internal wall 2	2.568	21	21	0	1.83486	4.71[a]
Internal wall 3	3.984	21	21	0	1.83486	7.31[a]
Internal wall above door 4	.32	21	21	0	1.83486	.59[a]
Window	1.858	21	10	11	4.7	96.06[a]
Door	1.6	21	21	0	1.675	2.68[a]
Total heat loss through fabric						463.99
Q_V = 1 x (5.67) x 11 x 0.33 = 20.58 watts lost through ventilation						20.58[b]
Total Heat Loss through fabric and ventilation heat loss at 10^{o}C						484.57

Note. Standard equations from Metric Handbook Planning and Design Data (Littlefield 2008)

[a] Surface area m^2 X (inside ^{o}C – outside ^{o}C) X U-value of fabric = watts lost

[b] (Q_V) = V_a X volume X ΔT X ρC/3600

Where

Q_V = heat loss or gain in watts

V_a = ventilation rate in air changes per hour (ac/h)

ΔT = internal/external air temperature difference ^{o}C

ρC = volumetric heat capacity of air = 1200$Jm^{-3}K^{-1}$

Table 4.3

Heat Loss through Building Fabric at an Internal Temperature of 21°C, with an External Temperature of 5.3 °C, the Lowest Monthly Mean Temperature

Surface	Area m^2	Inside Temp °C	Outside Temp °C	ΔT °C	U-value	Loss in Watts
Roof	6.5268	21	5.3	15.7	1.123	115.07[a]
Floor	6.5268	21	21	0	0.827	5.4[a]
External wall (East)	8.63	21	5.3	15.7	1.7556	237.87[a]
External wall (South)	4.56	21	5.3	15.7	1.7556	125.69[a]
Internal wall 1	6.504	21	21	0	1.83486	11.9[a]
Internal wall 2	2.568	21	21	0	1.83486	4.71[a]
Internal wall 3	3.984	21	21	0	1.83486	7.31[a]
Internal wall above door 4	.32	21	19	2	1.83486	1.17[a]
Window	1.858	21	5.3	15.7	4.7	137.10[a]
Door	1.6	21	19	2	1.675	5.36[a]
Total heat loss through fabric						651.58
(Q_V) = 1 x (5.67) x 15.7 x 0.33 = 29.38 watts lost through ventilation						29.38 [b]
Total Heat Loss through fabric and ventilation heat loss at 5.3°C						681

Note. Standard equations from Metric Handbook Planning and Design Data (Littlefield 2008)

[a] Surface area m^2 X (inside °C – outside °C) X U-value of fabric = watts lost

[b] $(Q_V) = V_a$ X volume X ΔT X $\rho C/3600$

Where

Q_V = heat loss or gain in watts

V_a = ventilation rate in air changes per hour (ac/h)

ΔT = internal/external air temperature difference °C

ρC = volumetric heat capacity of air = $1200 Jm^{-3}K^{-1}$

Using the cost of electricity in cents per kWh, the cost of using electricity to maintain the room temperature at 21^{o}C was calculated for the annual mean and the December mean temperature. A monthly and annual cost was calculated for electricity use of 0.5hrs, 1hr, 1.5hrs, and 2hrs per day at an external temperature of 10^{o}C. These intervals were chosen to replicate the use of portable electric radiators to supplement the heating system as observed at Sligo Town Hall.

According to the SEAI, the delivered energy cost of electricity when building energy use is greater than or equal to 15,000 kWh per annum, is 18.24 cent/kWh (SEAI, 2015). This energy use band "Band DE", has a reduced rate due to the large quantity of energy used annually. The electrical energy used (E) in kWh is calculated by multiplying the power in watts [P(W)] by the time in hours [t(hr.)] and dividing it by 1000. The resulting figure is then multiplied by the cost in cent per kilowatt hour to get the cost of maintaining an internal temperature of 21^{o}C when the external temperature is 10^{o}C. Table 4.4 shows the cost for different use profiles.

E(kWh) =

P(W) × t(hr.) / 1000

484.57 × 10 / 1000

4.85 kWh of energy is used in 10 hours

Cost = 4.85 kWh x 18.24 cent/kWh

= 88.46 cent per month.

Table 4.4

Electrical Heating Cost per Day and per Year for Test Room at the Annual Mean Temperature of 10^{o}C

Time per day	Time per month	Cost per month	Cost per year
.5 hrs.	10 hrs.	€0.88	€10.56
1 hr.	20 hrs.	€1.76	€24.30
1.5 hrs.	30 hrs.	€2.64	€31.68
2 hrs.	40 hrs.	€3.52	€42.24

The monthly electricity cost to maintain an internal temperature of 21^{o}C using a portable electric heater for 0.5hrs, 1hr, 1.5hrs, and 2hrs was also calculated at an external temperature of 5.3^{o}C, the resulting figures are listed in table 4.5. The inclusion of the December figures was to acknowledge building use scenarios where electrical radiators are only used in very cold weather.

It should be noted that the test room is smaller than most public building rooms, has single glazed windows, and is a single room.

E(kWh) =

P(W) × t(hr.) / 1000

681× 10 / 1000

6.81 kWh of energy is used in 10 hours

Cost = 6.81 kWh x 18.24 cent/kWh

=124.21 cent per month.

Table 4.5

Electrical Heating Cost per Day and per Year for Test Room at the Lowest Annual Mean Temperature of 5.3^{o}C (December)

Time per day	Time per month	Cost per month
.5 hrs.	10 hrs.	€1.24
1 hr.	20 hrs.	€2.48
1.5 hrs.	30 hrs.	€3.72
2 hrs.	40 hrs.	€4.96

Following the heat loss and cost calculations, the actual energy load and total annual consumption was calculated using; the number of degree days below 15.5^{o}C at Finner AWS, the efficiency of the oil heating system, and the number of heating hours per year. The mean monthly temperatures at Finner Automated Weather Station for the years 2012, 2013, 2014, and 2015 are collected in table 4.6. The number of heating hours was based on the approximate number of annual business days at the Sligo Town Hall.

Table 4.6

Degree Days below 15.5 Degree Celsius for Finner

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2015	317	299	287	216	186	107	70	65	N/A	N/A	N/A	N/A	N/A
2014	307	272	260	159	127	62	32	62	67	138	229	279	1993
2013	309	287	368	253	179	74	23	31	N/A	123	N/A	N/A	N/A
2012	277	225	N/A	253	151	99	71	33	96	209	267	303	N/A

Note. Degree Days collected at Finner Automatic Weather Station (Met Éireann, 2015)

The Annual Energy Load is calculated using the total fabric and ventilation heat loss (QT), the internal design temperature (Ti), the outside design temperature (TO), and the heating degree days (DD). At a room temperature of 22^{o}C and an external temperature of 10^{o}C, the fabric heat loss is 464 watts and the ventilation loss is 20.58 watts, resulting in a total heat loss of 485 watts. The degree days figure used is from the 2014 readings at Finner Automated Weather Station and the number of hours is eight per day.

Annual energy load =

[[QT ÷ (Ti-To)] x DD x 8] / 1000 (kWh)

[(485/21-10) X 1993 X 8] / 1000 (kWh)

702.97 kWh

The actual energy load relates to the system seasonal efficiency (η) which is 70% for an oil heating system (Arbon & Kilbane-Dawe, 2013). Boilers are not 100% efficient at converting energy in an oil form to building heating energy, heat can be lost through flue gases and through the variation in use and equipment, this reduced figure must be considered in calculating the actual energy load (Arbon & Kilbane-Dawe, 2013).

Actual energy load =

[[QT ÷ (Ti-To)] × DD × 8 x (1 ÷ η)] ÷ 1000 (kWh)

[(484/21-10) X 1993 X 8 X (1/.7)] / 1000 (kWh)

1004 kWh

4.2 Design of Experiment

Building the overall experimental conditions required a number of different pieces of equipment, these included temperature reading and recording equipment, a heating device, and storage containers for test materials. A number of different approaches were considered for each of these systems and were disregarded with consideration of cost and engineering concerns.

4.3 PCM Choice and Manufacture

The choice of MPCM product was informed by the following factors; product form, manufacturer customer assistance, product information, and cost.

Microencapsulated PCM cannot currently be purchased from a retailer or manufacturer in Ireland. MikroCaps in Slovenia and Microtek in the USA were contacted in relation to the supply of PCM. Both companies were willing to supply 1kg of MPCM for educational purposes but this would not have been sufficient for the proposed field experiment. A minimum purchasable quantity of 20kg cost €500 from MikroCaps and five gallons costing $35 per pound from Microtek was quoted, leading to a similar cost price. MikroCaps would supply the MPCM in suspension while Mikrotek would supply the MPCM in powder form.

MikroCaps in Slovenia was chosen as supplier due to the technical guidance provided by Dejan Stefanec and Aljoša Vrhunec, and by Felix Pawelz and Andreas Larz at Rubitherm, Mikrocaps supplier of PCM. Mr. Stefanec provided feedback on a number of experiment designs and provided technical advice on the choice of heat of fusion temperature for the PCM. Mr. Stefanec clarified that MikroCaps microencapsulate phase change material but they do not produce it. The phase change material would come from Rubitherm and would need to be from their ‘RT’ line of PCM. The PCM supply and microencapsulation process for Microtek was unclear. In addition to technical assistance, the pre prepared suspension by MikroCaps would remove the human error of the researcher in creating the final suspension.

The process of MPCM slurry production at Mikrocaps was limited by cost constraints and molarity. In order to create MPCM capsules Mikrocaps encapsulate the PCM in a polymer coating resulting in an impermeable membrane around the PCM (MikroCaps, 2015). This creates a slurry liquid of forty percent MPCM capsules in water. The solution is then subjected to spray drying to remove the liquid resulting in a MPCM powder. Should a higher molarity slurry be required then MPCM capsule powder is added to the forty percent MPCM slurry to increase its concentration (Stefanec, personal communication, February 6, 2015).

In this experiment the forty percent solution was used due to financial and time constraints, an increase in molarity may have also have been difficult to heat to phase change temperature due to reduced convection currents and increased thermal storage overall.

The choice of latent heat temperature was defined by the raw base product supplier and by the heating cycle likely to occur in the test fluid. Challenges of heat transfer, maximum radiator heat output, and location of PCM relative to the heat location could prevent sufficient transfer of thermal energy. It was required that the

PCM would not need a very high temperature to initiate phase change, but would need to be high enough to release additional heat at a temperature which would reduce the cooling curve of the liquid. The MPCM slurry also needed not to have a very low phase change temperature as it could slow the initial heating of the room then release heat at too low a temperature to benefit room occupants. PCM phase change temperature needed to be low enough that the radiator would emit heat at that temperature for a long enough period that would allow the PCM to absorb a sufficient amount of heat to impact the room temperature during the cooling phase. A temperature of 35^{o}C was chosen in a high heat capacity PCM, following consultation with the supplier (Stefanec, personal communication, March 2nd, 2015), the properties of the PCM (Rubitherm RT35HC) are outlined in table 4.7 and the properties of the MPCM slurry (MikroCapsPCM35) are listed in table 4.8, the original data sheets are located in Appendix C and D respectively.

The microencapsulation process required four weeks as the raw material Rubitherm RT35HC was shipped from Berlin, Germany, to Ljubljana, Slovenia. The minimum purchasable quantity of microencapsulated phase change material slurry (MPCMS), twenty liters was ordered and shipped to Dublin Institute of Technology, Ireland.

Table 4.7

Typical Values for Material Properties of PCM Rubitherm RT35HC

Material Property	Typical Values
Melting area	34-36°C main peak:35
Congealing area	36-34°C main peak:35
Heat storage capacity ± 7,5%	240kJ/kg [a]
Combination of latent and sensible heat in a temperature range of 27°C to42 °C.	67Wh/kg
Specific heat capacity	2kJ/kg·K]
Density solid at 25°C	0,88kg/l]
Density liquid at 40°C	0,77kg/l
Heat conductivity (both phases)	0,2W/(m·K)
Volume expansion	12%
Flash point (PCM)	177°C
Max. operation temperature	70°C

Note. Data collected from Rubitherm RT35HC Data Sheet (Rubitherm, 2015)

[a] Heat storage capacity was measured with 3-layer-calorimeter.

Table 4.8

Material Properties of MikroCapsPCM35, an Aqueous Dispersion of Microencapsulated Paraffin Wax

Composition	Classification	Phase Change Materials Microcapsule dispersion
	Type of Membrane	Melamine-formaldehyde
	Type of PCM	Paraffin wax
Technical Data	PCM content in the dispersion	25-30%
	PCM content in dry capsule	80-85 %
	Dry content in the dispersion	35-38%
	PCM melting area	33-37 °C
	Heat storage capacity (of dried microcapsules)	190-200 J/g
	Heat storage capacity of slurry	65 J/g
	PH	7,0-9,0
	Density	900-970 g/cm^3
	Viscosity (at 25°C)	10-500 cPs
	Appearance	White slurry
	Average particles size	1-20 µm
Storage and Handling	Storage	Store at an even temperature between +5°C and 35°C.
	Use	Slurry may separate after
	Shelf life	6 months – stir if this occurs

Note. Data collected from MikroCaps PCM35 Data Sheet (MikroCaps, 2015)

4.4 Heat Energy Calculations for Tested Liquids

The specific heat capacity of the micro encapsulated phase change material (MPCMS) is 65J/g. while the specific heat capacity of water is 4.18J/g (The Engineering ToolBox, 2015). The storage capacity of 20kg of MPCM slurry and water can be calculated by calculating the amount of heat required to heat the test fluid by 1^{o}C. The amount of heat in joules (Q) is calculated using the specific heat in joules per gram (C_p) and the mass of the material.

Q =

c_p m

65j x (20 x 1000)

1300000j would be required to change the temperature of the MPCM slurry by 1^oC.

Q =

c_p m

4.18j x (20 x 1000)

83600j would be required to change the temperature of the water by 1^oC.

An approximation of test radiator heat output in watts can be calculated to estimate the energy supplied by the radiator. The calculation of free convection transferred over time (q) in watts is calculated using the heat transfer area of the surface in meters squared (A), the convective heat transfer coefficient of the process in watts per meter squared degree Celsius (h_c), and the temperature difference between the surface and the estimated room temperature without heating (dT). The convective heat transfer coefficient used for gases and dry vapours can be between 5-37 (Engineers Edge, 2015), for this study a conservative estimate is taken and 6 is presumed as the convective heat transfer coefficient of the air in the room.

q =

h_c A dT

6 x 1.632 x (60 (radiator surface temperature) -15 (room temp without heating)

440.64W

In order to estimate if the radiator emits enough heat to change the temperature of the MPCM slurry, time must be considered. If 1W is equal to 1j/s, then 440.64W is 440.64j/s. Multiplying this figure by the number of seconds in an hour equals 1586304j/s which could change the MPCM slurry by more than 1^{o}C.

4.5 Thermometers

The collection of data would need to happen at specific intervals and the thermometers would need to have a similar tolerance to minimize error. The two types of thermometers were purchased from Texas Instrument and were manufactured in the same batches so that the tolerances would be the same, and any inaccuracies would be consistent. The data collection was set at three second intervals collecting on a two gigabyte mini secure digital (SD) card. The product information for the two sensor types is collected in table 4.9 (Texas Instruments, 2015).

Table 4.9

Product Information for Sensors used in Thermometer System (Texas Instruments, 2015)

Product Information	LM35DZ/NOPB Air Temp Sensor	LM35DT/NOPB IC, Surface Temp Sensor
IC Output Type:	Voltage	Voltage
MSL:	MSL 1 - Unlimited	MSL 1 - Unlimited
No. of Pins	3	3
Packaging	Each	Each
SVHC	No SVHC (15-Jun-2015)	No SVHC (15-Jun-2015)
Sensing Accuracy Range	± 0.4°C	± 0.6°C
Sensing Temperature Max	+100°C	+100°C
Sensing Temperature Min	+2°C	0°C
Sensor Case Style	TO-92	TO-220
Supply Voltage Max	30V	30V
Supply Voltage Min	4V	4V

Note. Data collected from product specifications (Texas Instruments, 2015)

A temperature reading and recording system was built by Mr. Peter Doyle, a Research and Development Engineer at Novaerus Inc. The system consisted of a memory card storage backed micro controller connected to five thermometers, three atmospheric thermometers (no. 2, 3, and 4) and two surface temperature thermometers (no. 1, and 5) with a number of cable lengths. Thermometers numbered 1, 4, and 5 measured 1150mm (45") and thermometers numbered 2 and 3 measured 1900mm (75"). The temperature and recording system schematic is shown in figure 4.1, and the built thermometer assembly can be seen in figure 4.2.

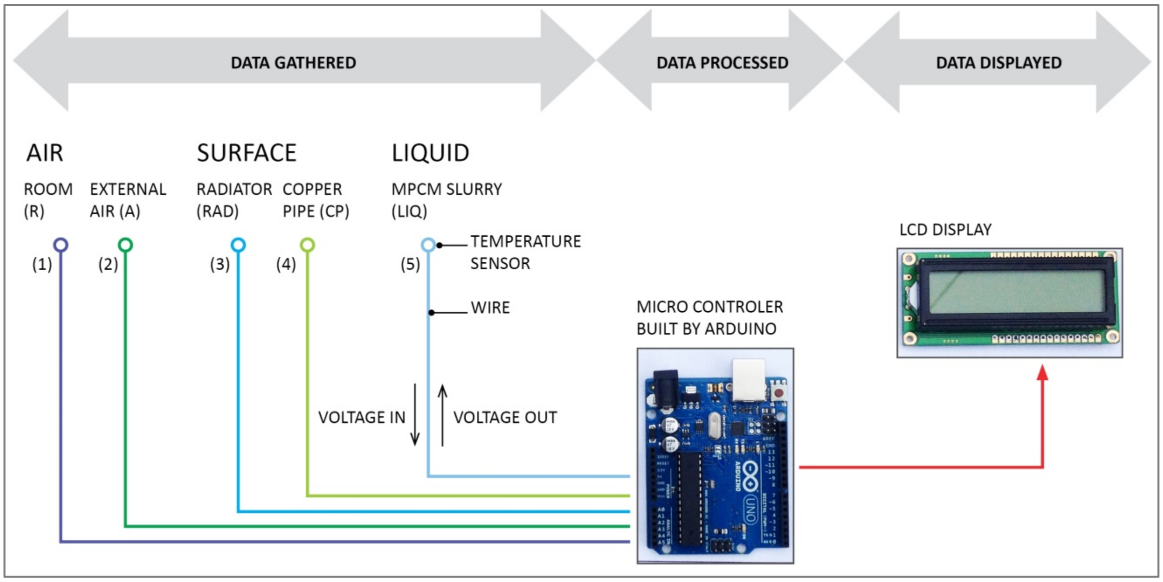


Figure 4.1 Thermometer schematic

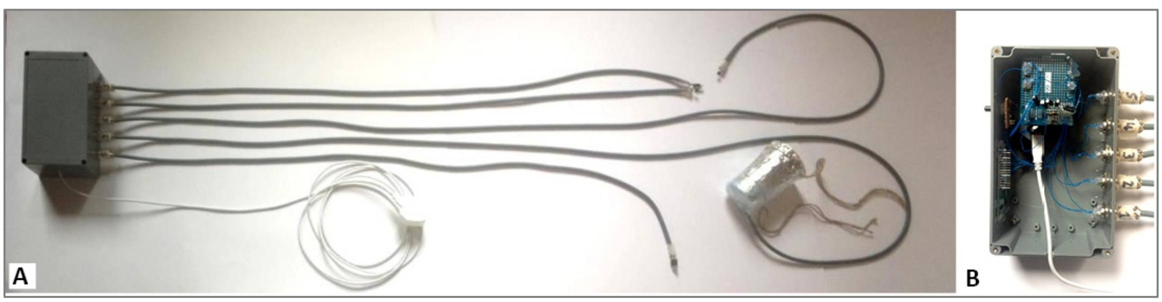


Figure 4.2 Images showing the built thermometer assembly, A) the micro controller housing and sensor cables, and B) the exposed microcontroller

4.6 Radiator

The base of the experiment required a heating element which could be used to replicate the typical heating scenario of a stone building in Ireland. The existing radiator located in the test structure is a single steel panel radiator. This radiator is flat, rectangular and long, unlike the cast iron radiators found in many historical and protected structures.

The radiator is also gravity fed from an oil fired stove located in the kitchen. The test room heating is entirely reliant on the stove operating hours. This system for the purpose of this study is unpredictable and difficult to control due to building being in continual use. It was decided that a system with a greater level of control and a profile more similar to that of a cast iron radiator should be used.

The heating element would need to fulfil certain criteria. It would need a simple on/off control mechanism, a means to heat the test liquid from its heat and an appropriate design for use in a small room of 5.67m^2.

Gas heaters were rejected due to their requirement for good ventilation and unsuitable shapes. Fan-forced ceramic heaters, radiant heaters, and panel heaters were also rejected due to their unsuitable shapes and heating elements. An electric convection radiator was chosen due to its shape, use of a sealed fluid to manage heat distribution, and ease in transport, allowing for the construction of containers to be done elsewhere. Its use of electricity meant that the radiators could be timed to come on at defined intervals.

An existing oil filled radiator was used to evaluate the potential for a test material to be added. An oil filled radiator is a convection heater; the oil is used as a heat reservoir and is not burnt as a fuel.

In evaluating the possible model of radiator it was established that the gap between the fins would need to be substantial enough to accommodate a volume of liquid while allowing the air to circulate and be heated by convection. Minimizing the direct contact of any containers would also prevent safety issues or any leaking of fluid due to heat related damage.

The size of the electric oil filled radiator was sized using the radiator center (2015) radiator heat calculator. The calculator recommended a 1695W radiator. It was considered that a new Dimplex 2kw radiator could be used and the temperature would be set so as to replicate a central heating system temperature profile.

An issue encountered was the gaps between fins on new oil radiators. While Dimplex on enquiry had listed the fins as being 50mm center to center, on inspection all of their new radiators were 40mm center to center.

Searching of homeware and online retailers indicated that radiators with 50mm fin gaps are no longer being produced, it was decided that the existing radiator would be used. A visual inspection of the trial radiator concluded that although the radiator is approximately ten years old it is still heating evenly and it was decided that inefficiencies in its heating profile would not affect the results outcome as they would likely be consistent over the whole of the experiment due to its good working order.

A traditional heating system has a flow of 90^{o}C and return temperature of 70oC (Donohoe, 2012). The high temperature posed concerns over container stability and safety, so a lower temperature range of between 40^{o}C and 50^{o}C was chosen, and a trial run was done on the radiator to determine if the proposed MPCMS containers could reach a high enough temperature to initiate phase change.

4.7 Container Fabrication

Twenty liters of test fluid would need to be accommodated either adjacent to, or on the radiator using containers which would be suitably heat resistant, strong, and unreactive to fluids. The containers would need to be close enough to absorb heat but not impede the functionality of the radiator.

It was observed that the majority of increase in room temperature generated was by convection of air from the radiator rising upwards. It was decided not to cover the radiator for heating and safety purposes.

Adjacent to the radiator and between the fins became the focus of efforts to add the fluid. Air would need to circulate and the surfaces would become quite hot so careful consideration was given to the type of container used. Figure 4.3 and 4.4 show the containers considered and their potential benefits and failings. The containers used in this experiment can be seen in figure 4.5.

COPPER PIPING

Advantages:
Conductive
Unreactive
Workable
Sealable with envelope fold
Could be placed between fins

Disadvantages:
Expensive €4.91/m
Large number of pipes required
Resulting large quantity of copper may influence results

Assessment method:
900mm copper pipes attached to radiator and heated
Cost calculation
Volumetric capacity calculation

Evaluation:
Inefficient space use
Complexity of construction
Cost
Would require 17.62m of 3/4inchpipe
Square steel tubes were also considered but welded base plates would be required and the finished tubes would be heavy.

FOIL POUCHES

Advantages:
Conductive
Light
Cheap
Flexible
Durable
Re-sealable screw top

Disadvantages:
Small (330ml or 11.16oz)

Assessment method:
CapriSun juice pouches
refilled with water and exposed to radiator heat

Evaluation:
Difficult to refill bags
Challenging overall construction due to small size

ICE CUBE BAGS

Advantages:
Minimal thermal resistance
Flexible
Designed to hold fluid in individual compartments
Could be hung between fins due to its narrow depth
Inexpensive

Disadvantages:
Fragile

Assessment method:
Visual evaluation
Empty ice cube bag attached to oil filled radiator and monitored during heating cycle

Evaluation:
Melted when exposed to 60ºC
More substantial/tougher ice bags could not be purchased.

ICE PACK COOLER

Advantages:
Rectangular shape
Compact
Durable
Structured

Disadvantages:
Existing cooler fluid included
Expensive
Opaque, no view of liquid

Assessment method:
Ice pack refilled with water and exposed to radiator heat

Evaluation:
Melted when exposed to radiator surface temperature

Figure 4.3 Test liquid container trial summary for copper pipes, icecube bags, foil pouches and ice pack coolers

PLASTIC BAG

Advantages:
Cheap
Fluid quantity could be controlled
Flexible size
Non-reactive
clear

Disadvantages:
No rigid structure
Unknown thermal resistance

Assessment method:
Variety of bag types evaluated for structure, volume and durability.
Most appropriate bag filled with water and exposed to radiator heat

Evaluation:
Sealapack Resealable Food Puches 8Pk
500ml bags – appropriate size, heat resistant to extremes of temperature due to its microwave safe freezer characteristics
safe
Tougher plastic due to reuse function.

PANEL OF BAG BETWEEN WIRE RACKS

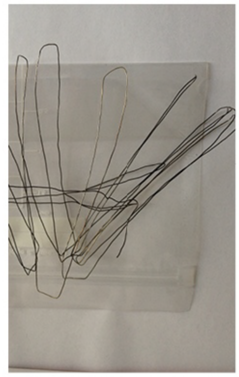
Advantages:
Solid
Suitable height 330mm
Cheap

Disadvantages:
Sharp welded joints
Time consuming construction

Assessment method:
11 packets of 3 cooling trays were purchased containing a total of 33 cooling trays at a cost of €77
Support legs were removed
Racks were tied with twine with a 25mm (1”) gap

Evaluation:
Bags punctured due to welding joints on one side of each rack. Solved by careful facing of racks
Structure put pressure on bags forcing liquid out.
Wooden discs inserted at top to prevent this

BAG IN WIRE MESH



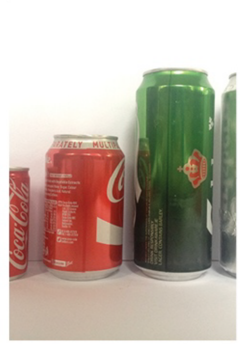
Advantages:
Flexible size
Conductive – may encourage heat flow from air around the radiator to the fluid contained in the bag
Inexpensive

Disadvantages:
Difficult to assemble
Time consuming construction
Difficult to alter bad contents

Assessment method:
Unable to construct in a reasonable time period

Evaluation:
Wire tested was too weak
Damage was done to bags by sharp wire edges

ALUMINUM CANS



Advantages:
Minimal material
Conductive
Cheap
Available in a variety of sizes 330ml(11oz), 500ml(17oz)
Uniform size
stackable

Disadvantages:
Sealing devices for cans were difficult to get.

Assessment method:
Aluminum cans filled with water and exposed to radiator heat

Evaluation:
Cans could be adequately sealed with duct tape

Figure 4.4 Test liquid container trial summary for plastic bags, panel of bag between wire racks, bag in wire mesh, and aluminum cans

Figure 4.5 Test liquid (MPCM slurry) shown A) in aluminum 500ml cans, B) in sandwich panels of two 500ml bags, and C) assembled on portable radiator

4.8 Radiator Setup Trial

A test was carried out with water to determine if the heat could transfer from the radiator into the cans and bags via conduction and convection. A surface temperature sensor was placed on the upper can and upper bag of the trial assembly, see figure 4.6. The radiator thermostat was set to 6 and switched on at 17:00. The rise in temperature was visually logged every 15 minutes. At 19:00 the radiator was switched off and the decrease in heat was visually recorded every 15 minutes for the next two hours until 21:00. The recorded data can be seen in table 4.10.

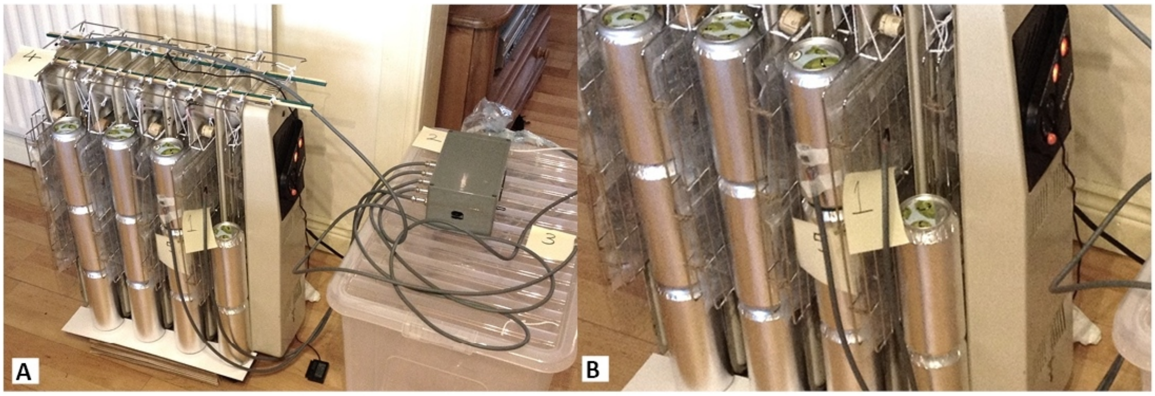


Figure 4.6 Radiator trial assembly (A) with a close up of sensor location show in (B)

Table 4.10

Surface Temperatures Recorded During Trial for Sensor 1 and Sensor 5

Time	Sensor 1 (^{O}C) Water filled bag	Sensor 5 (^{O}C) Water filled can
17:00	19	18
17.15	26	19
17:30	32	20
17:45	37	21
18:00	41	25
18.15	42	29
18.30	45	33
18.45	46	35
19:00	48	37
RADIATOR SWITCHED OFF		
19.15	47	39
19.30	43	38
19.45	38	37
20.00	36	36
20.15	34	35
20.30	33	34
20.45	32	33
21.00	31	32

The collected data showed that the surface of the bags and cans reached a high of 48^{O}C and 39 ^{O}C respectively, indicating a similar temperature for the contained fluid. It was surmised that this experimental assembly would provide a suitable structure for the proposed experiment.

4.9 Room Preparation

The test room was prepared four days before the experiment. The gravity fed radiator was switched off and four days were given to allow the thermal mass of the wall behind the radiator to lose its stored heat, this would prevent any stored heat emission to the room during the data collection period. Although the radiator was turned off, its feeding pipe still contained very hot water. Normally such feeding pipes are located in the floor, in this case due to the buildings age the pipes run along the length and width of the external wall in the room. It was not possible to stop hot water flowing through this pipe as it is solely controlled by the stove operation.

It was determined that the heat emitted by the pipe could possibly contribute to the room temperature while the stove was on. The pipe was insulated using RayShield® brand double bubble foil reflective insulation in order to reduce its heat output, shown in figure 4.7 part A.

The test room chosen for the experiment is facing due east. Originally having planned to do the experiment in March the azimuth of the suns angle had changed by May affecting the solar influence on the room.

Strong low angle sunlight was observed in the room prior to the experiment which increased the room temperature. To counteract the sun influence on the room temperature, aluminum foil was placed on all window panes to prevent sunlight entry to the room for the duration of the experiment. This intervention can be seen in figure 4.7, part B and C.

A sign was erected on the door to inform occupants that the room should not be entered and the door was secured using a leather tie and screw as the door has no lock.

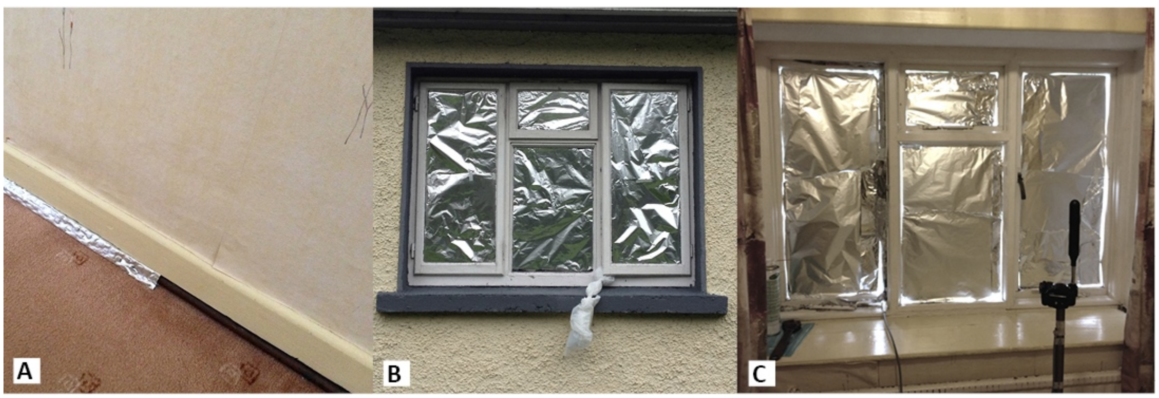


Figure 4.7 Rossinver building survey details showing (a) radiator supply pipe, (b) external thermometer Test Week 1, and (C) addition of aluminum foil to window interior

4.10 Experiment

A system using two container types was chosen based on the outcomes of the container trials. Container type 1 was the rack and bag system of two 500ml plastic bags sandwiched between two racks and hung from a flat scaffold resting on top of the radiator. Container type 2 was the 500ml aluminum cans, stacked and placed at alternating ends of each set of fins. These cans rested on a platform to support them at radiator height and were then restrained back to the scaffolding to ensure good contact between the fins and the can surface. The assembly stages for the addition of container types 1 and 2 to the radiator can be seen in figure 4.8 and figure 4.9. The radiator assembly equipment is shown in figure 4.10 and the assembled test setup for Test Week 3 is shown in figure 4.11.

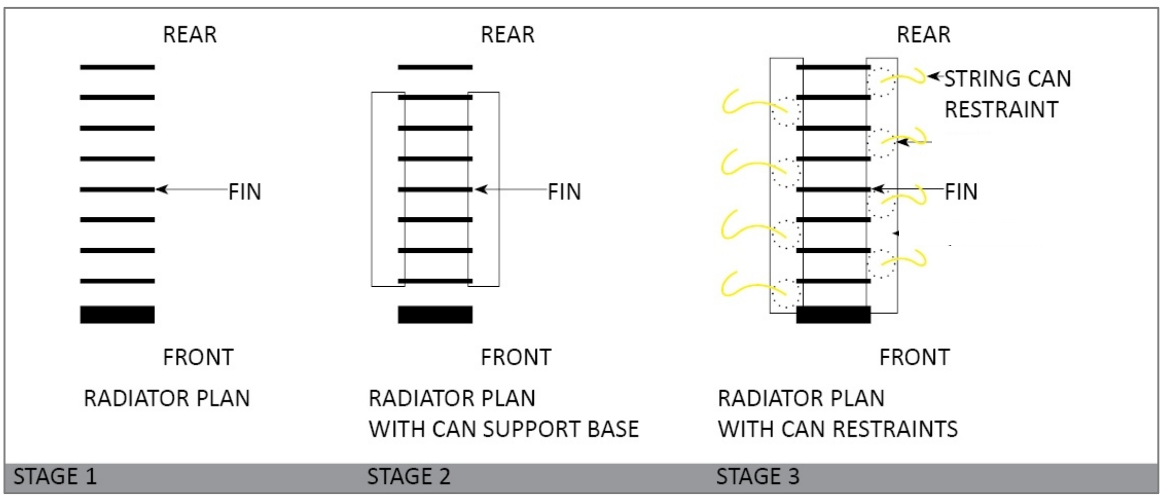


Figure 4.8 Radiator assembly stages 1, 2, and 3 for test weeks 3 and 4 (Doyle, 2015)

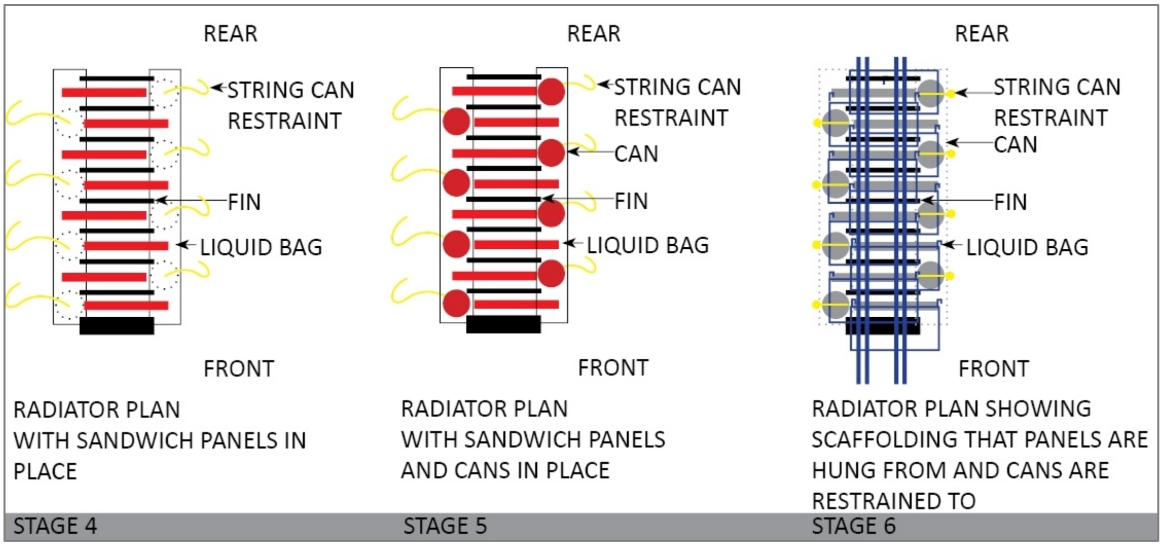


Figure 4.9 Radiator assembly stages 4, 5, and 5 for test weeks 3 and 4

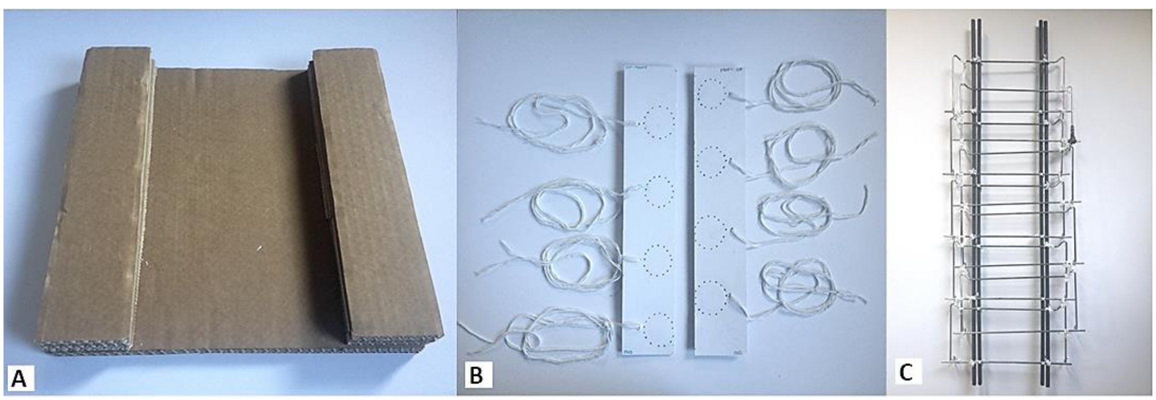


Figure 4.10 Radiator assembly equipment, A) support base for cans, B) positioning baseboard and restraints for cans, and C) structure for hanging sandwich panels and restraining cans

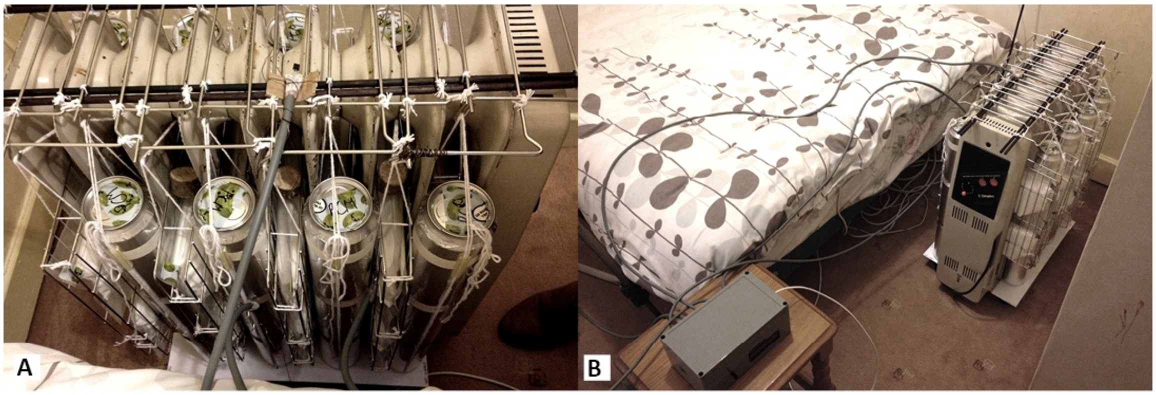


Figure 4.11 Radiator assembly Test Week 3

4.11 Independent Variable Treatment

Treatment no. 1 was the application of no heat to the room, this test week would act as the control. This treatment was to confirm that the addition of a heating system results in an increase in room temperature. Treatment no. 2 was the addition of a radiator to the room. The radiator was timed to switch on for two hours every six hours, providing two hours of heating and four hours without heating. This cycle would run four times in the twenty four hour test day period and at the same time each day. Treatment no. 3 test week involved the addition of MPCM in a slurry form to the radiator, followed by treatment no. 4 which required the addition of water only to the radiator. The addition of a water test was to assess if the addition of MPCM caused any change to the dependant variable beyond any change caused by water alone. During the testing periods of treatment no.3 and treatment no.4 the radiator temperature, heating and cooling schedule, position and distance from the dependant variable sensor remained consistent. The independent variable treatments and schedule of testing are summarised in table 4.11.

Table 4.11

Independent Variables Treatment Test Order and Scheduling

Period	Treatment	Daily Heating Schedule	Daily Cooling Schedule	Daily Sensor timer schedule
Week 1	No radiator	12:00 – 14:00	14:00 – 18:00	11.30 – 11:00
		18:00 – 20:00	20:00 – 00:00	
		00:00 – 02:00	02:00 – 06:00	
		06:00 – 08:00	08:00 – 12:00	
Week 2	Radiator only	12:00 – 14:00	14:00 – 18:00	11.30 – 11:00
		18:00 – 20:00	20:00 – 00:00	
		00:00 – 02:00	02:00 – 06:00	
		06:00 – 08:00	08:00 – 12:00	
Week 3	Radiator with 20 litres of MPCM slurry	12:00 – 14:00	14:00 – 18:00	11.30 – 11:00
		18:00 – 20:00	20:00 – 00:00	
		00:00 – 02:00	02:00 – 06:00	
		06:00 – 08:00	08:00 – 12:00	
Week 4	Radiator with 20 litres of water	12:00 – 14:00	14:00 – 18:00	11.30 – 11:00
		18:00 – 20:00	20:00 – 00:00	
		00:00 – 02:00	02:00 – 06:00	
		06:00 – 08:00	08:00 – 12:00	

4.12 Data Acquisition

The experiment was run day and night during the testing periods. The radiator was switched on for two hours and the room was allowed to cool for four hours before the radiator switched on again. This cycle was repeated four times in each 24hour period of the experiment.

This schedule was chosen to; observe the temperature swings generated by the heating and heat loss of the test room, provide a reasonable quantity of time for the test liquid to absorb heat, and to maximize the number of cycles observed.

Thermometer locations would be consistent across the four weeks for two of the five sensors, the other three would gather temperature data specific to that week. The locations of thermometers for each test week are listed and illustrated in table 4.12 and figures 4.12, 4.13, 4.14, 4.15, and 4.16.

Table 4.12

Thermometer Position for Each Test Week

Thermometer	Week 1	Week 2	Week 3	Week 4 (repeat)
1	Room temp	Room temp	Can Temp (surface)	Can Temp (surface)
2	Outside Temp	Outside Temp	Outside Temp	Outside Temp
3	Pipe adjacent	Room Temp	Radiator Temp	Radiator Temp
4	Room Temp	Room Temp	Room Temp	Room Temp
5	Insulated pipe (surface)	Insulated pipe (surface)	Bag Temp (surface)	Bag Temp (surface)

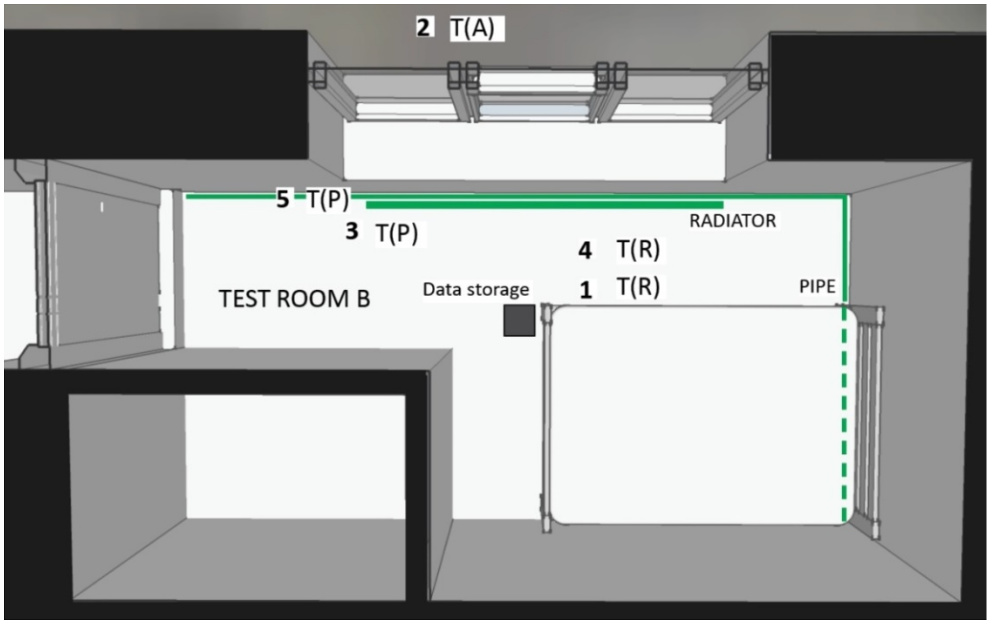


Figure 4.12 Test room arrangement for Test Week 1 showing thermometer locations

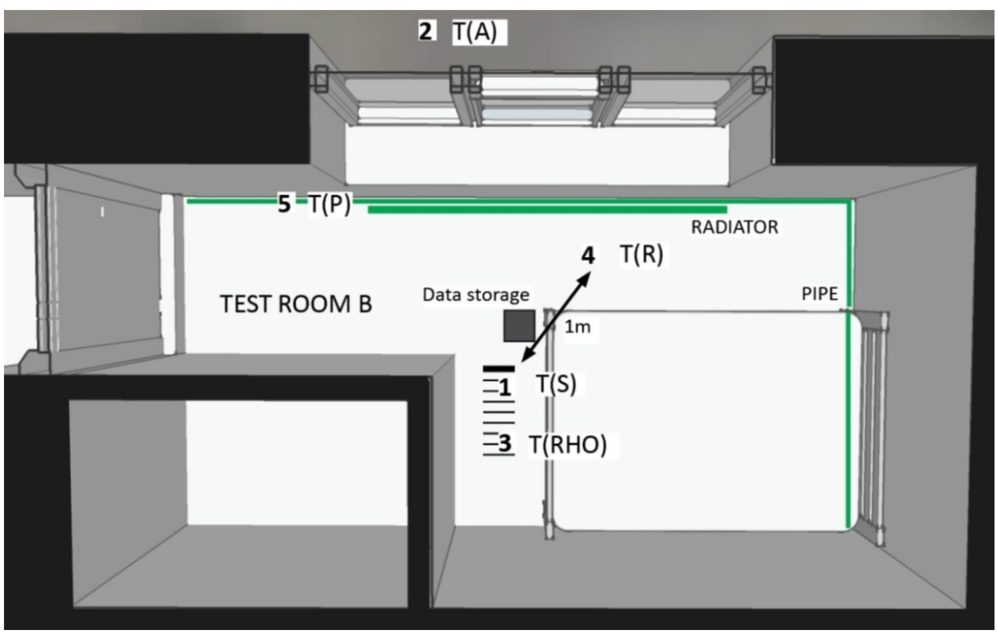


Figure 4.13 Test room arrangement for Test Week 2 showing thermometer locations and radiator location

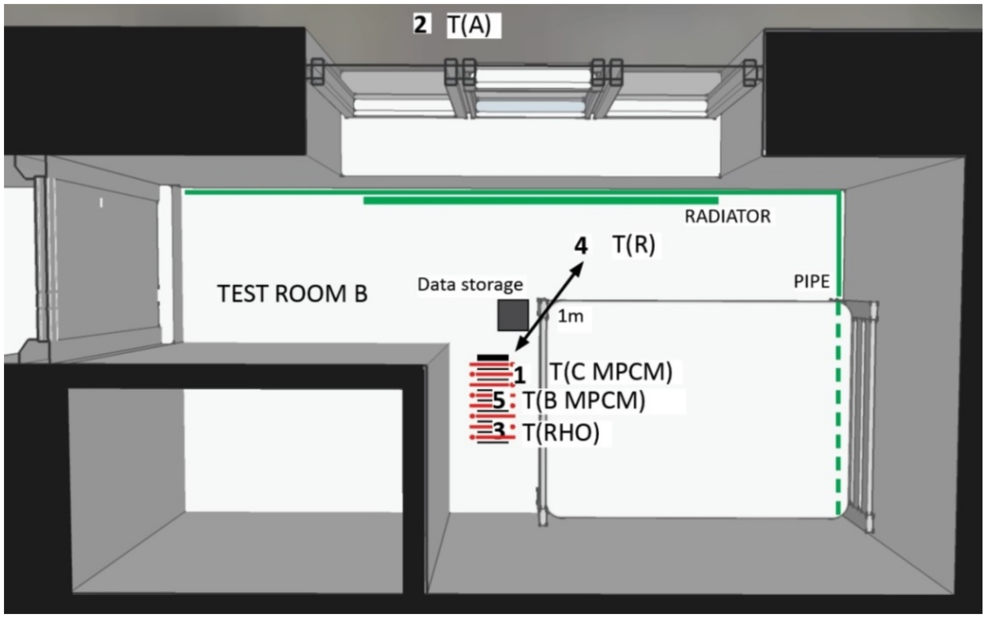


Figure 4.14 Test room arrangement for Test Week 3 showing thermometer locations and MPCM slurry treated radiator location

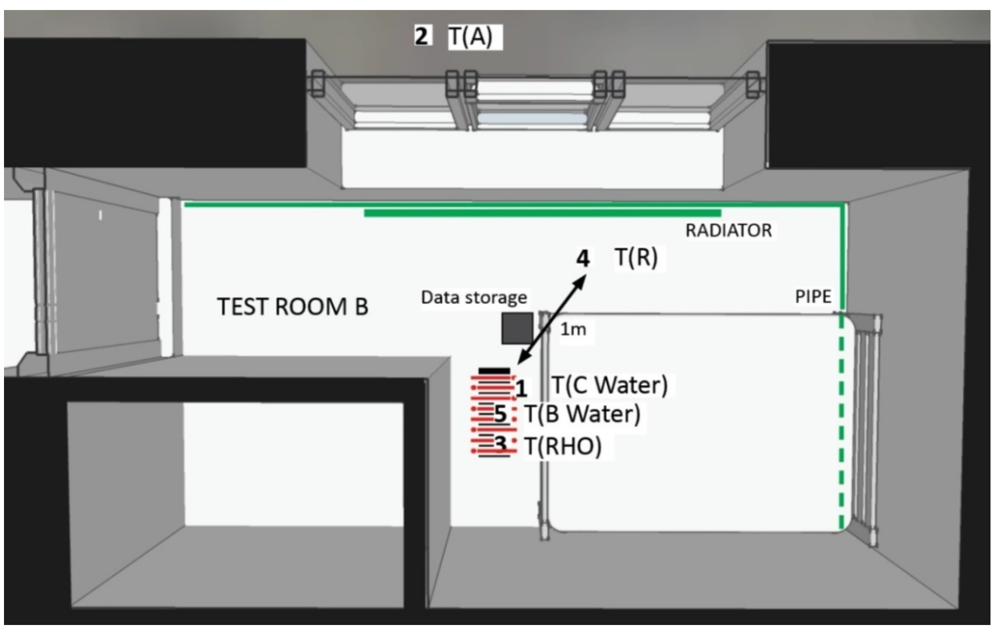


Figure 4.15 Test room arrangement for Test Week 4 showing thermometer locations and MPCM slurry treated radiator location

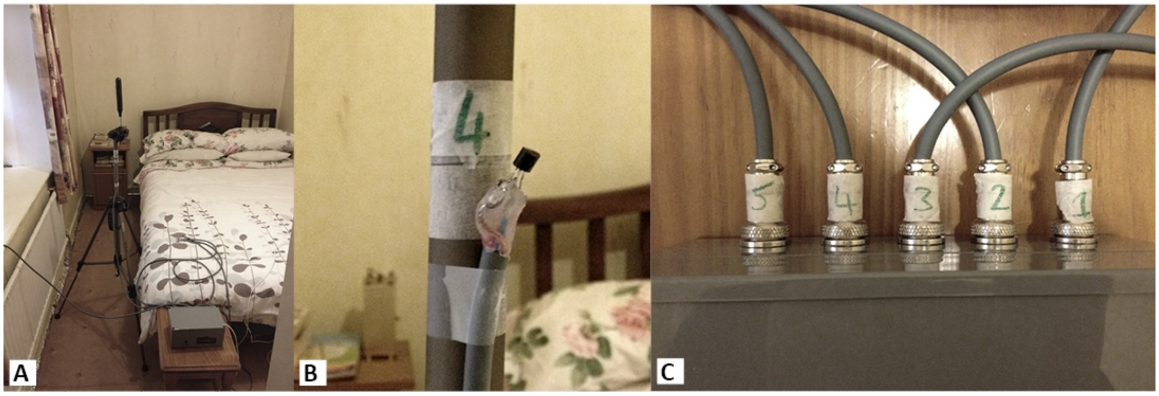


Figure 4.16 Test Room setup showing A) the Test Room, B) thermometer no.4 at 1m, and C) thermometer cable numbers

4.13 Data Acquisition Schedule

The experiment would be conducted on a weekly basis, data would be collected on a Monday and the test setup altered as planned. This would result in six days of uninterrupted data to be used for analysis. The researcher anticipated running the test over four weeks, the actual test dates are listed below in table 4.13.

Table 4.13

Actual Test Dates Where Data was Logged and used for Analysis

Test Day	Week 1: Water	Week 2: Radiator	Week 3: Radiator and MPCM slurry	Week 4: Radiator and water	Week 4: Radiator and water (repeated)
Setup Change	18 May 2015	25 May 2015	01 June 2015	08 June 2015	N/A
1	19 May 2015	26 May 2015	02 June 2015	09 June 2015	28 July 2015
2	20 May 2015	27 May 2015	03 June 2015	10 June 2015	29 July 2015
3	21 May 2015	28 May 2015	04 June 2015	11 June 2015	30 July 2015
4	22 May 2015	29 May 2015	05 June 2015	12 June 2015	31 July 2015
5	23 May 2015	30 May 2015	06 June 2015	13 June 2015	01 Aug 2015
6	24 May 2015	31 May 2015	07 June 2015	14 June 2015	28 Aug 2015

4.14 Data Collection Problem Test Week 4, Thermometer no.5

During Test Week 4 of the experiment where water was the treatment, the data logs collected at the end of the six days were irregular in size and did not add up to the same number of data entries as recorded in previous weeks.

It appeared that an error occurred with one of the thermostats disrupting the system and forcing it to restart creating a new log. On examination it was observed that the glue on thermometer No. 5 was melted. This thermometer had been attached sideways to a bag within a sandwich panel hung between the radiator fins.

It was determined that the most likely cause of the corrupted data was that during the heating cycle the glue melted and pushed the thermometer wires together, shorting the circuit, the thermometer can be seen in figure 4.17.

Following discussions with advisers Test Week 4 was repeated in order to collect a complete set of data for the water treatment scenario. Thermometer No. 5 was not reused.

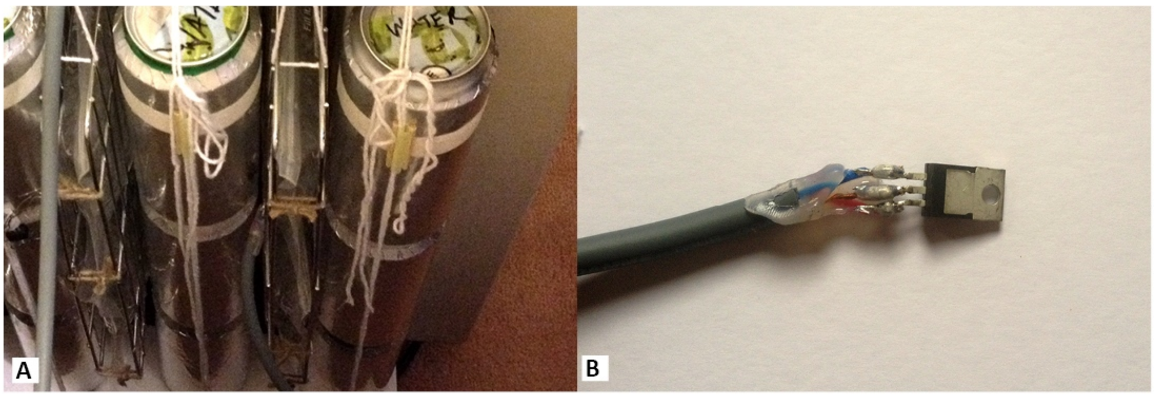


Figure 4.17 Thermometer no 5 shown A) attached to bag of water, and B) to have had issues with its glue melting

4.15 Data Collection Problem with Thermometer no.2

The influence of the eastern sunlight on thermometer no. 2 became apparent on inspection of the first week of data collected, a spike in the temperature readings taken by the external thermometer was identified during the early morning hours. External temperatures should be taken in the shade, and it had been planned that the experiment would be performed during the winter when very little sunlight would shine on the building and the temperatures would be low. The experiment was actually conducted in the spring and summer resulting in a change in azimuth and the exposure of the thermometer to direct sunlight. The morning sun exposure created a substantial spike in temperatures recorded by thermometer no. 2 affecting the overall means and range of temperatures collected.

The position of thermometer was altered, and placed under the window eve to provide all possible protection from the morning sun within the limits of the length of the thermometer cable. The white plastic bag was replaced by a plastic aluminum covered, open to the air container. The thermometer was also cover in resin, and allowed to dry and then placed in the plastic container. The two types of thermometer and covering applied to thermometer no. 2 are shown in figure 4.18.

Following the collection of irregular data, it was decided that additional weather data should be included in the findings. Finner Automatic Weather station (AWS) is located 20 kilometers from Rossinver on Finner Army Camp, Ballyshannon, Co. Donegal. The current AWS was installed on November 1st, 2010 replacing an existing AWS which had collected weather data since April 1996. It is located at 54°29’38” North and 08°14’35” West, thirty three meters above mean sea level and is maintained by Met Éireann, the Irish National Meteorological Service (Met Éireann, 2015).

Finner AWS collects, air temperature, wind speed and direction, rainfall, grass temperature, atmospheric pressure, relative humidity, global radiation, cloud height and amount and present weather. For the purpose of this study air temperature was included in the analysis.

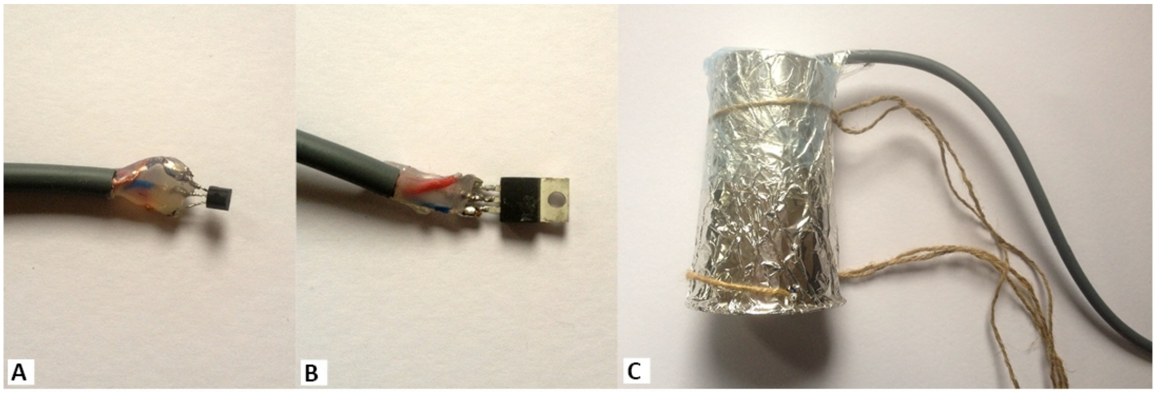


Figure 4.18 Image showing A) the air temperature sensor, B) the surface temperature sensor, and C) the cover applied to thermometer no.2 after spikes were observed

4.16 Summary

This chapter expanded on the basis for this case study, identifying the heat losses from a room in a historical building, and quantifying the financial implications of using electric heaters to supplement heating systems and schedules such as the system in place at Sligo Town Hall.

Further detail was given on the field experiment in terms of the development of equipment, choice of PCM, schedule design, and problems encountered during its operation period.

CHAPTER 5 RESULTS AND DATA ANALYSIS

After recording data under the conditions previously illustrated in chapters 3 and 4, analysis was performed using graphs and statistics to identify features of the data. The raw dataset can be viewed in Appendix E. The findings of this analysis, which are discussed in this chapter, can briefly be described as follows:

1. The weather and radiator supply pipe did contribute to changes in room temperature during Test Week 1.

2. The shape of the room temperature cooling curve was altered by the treatments to the heating system.

3. The standard deviation of the temperature values for Test Weeks 3 and 4 were found to be smaller than that of Test Week 2.

4. The cooling curve of the can surface during Test Week 3 showed evidence of latent heat behaviour.

5. Test Week 3 and 4 showed a reduction in the number of heating cycles required to heat the test room to a set thermostatic minimum temperature over time.

6. The financial implications of a reduction in heating cycles were calculated indicating a financial saving with the use of an augmented heating system.

5.1 An Overview of Test Week One, Two, Three, and Four

The data was originally captured into tab delimited text files, which were separated by day. In order to perform analysis, these were consolidated into comma separated value (CSV) files and organized by week for each experimental phase. The test room was monitored by a number of thermostats gathering data throughout the experimental period. The external temperatures recorded by thermometer no. 2 (TA) and internal temperatures recorded by thermometer no.4 (TR) are graphed in figure 5.1.

The T2 data for test week one showed a gentle rise overall along with small rises and falls in temperature. The small rises coincide with an increase in external temperatures during the day and a decrease during the night as the air cools. Test week two shows clear heating and cooling cycles, reaching highs of approximately 26^{o}C and lows of 18^{o}C. Week three shows heating and cooling cycles with a narrower range of temperatures than those of test week 2. Test week four shows defined heating and cooling cycles. The cycles appear regular and two have lower maximum and minimum temperatures then the radiator on its own, and the heating cycles appear to be more regular than those of test weeks two and three.

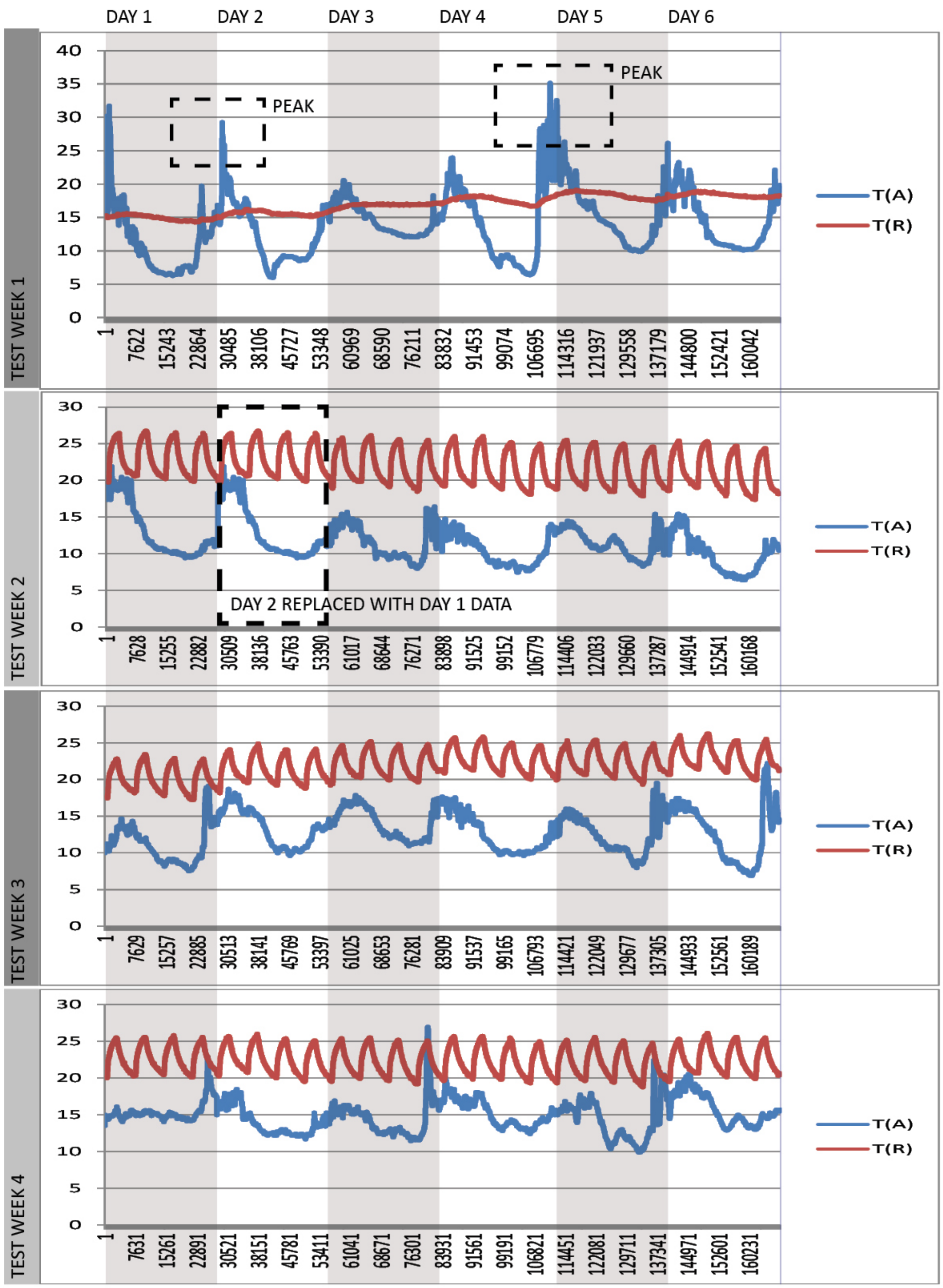


Figure 5.1 External (TA) and internal (TR) temperature data collected at Rossinver showing sunrise heat spikes, and heating and cooling cycles

The researcher observed temperature spikes in the T(A) data, these were determined to have been caused by the morning sun hitting the eastern side of the building. Having consulted with Mr. Doyle the researcher removed the white plastic covering and replaced it with a foil covered plastic container. The thermometer sensor was coated in resin to prevent water damage. A result of this intervention was that the data for that day was not collected by the sensor unit due to a possible overheat of the thermometer as the resin heated and cooled.

The researcher considered deleting test day two from each test week or replacing test day two of the radiator test week with test day one of the same week. The latter scenario was chosen as the removal of test day two from test week two would result in the removal of that day from all other test weeks, potentially removing important data. Test day one of that week was chosen as a substitute as the average external temperature was only 0.2^{o}C warmer than on test day two. It was reasoned that the heating and cooling cycle of the radiator test period would be predictable and consistent.

Despite the alteration to prevent sunrise related spikes, the data still showed substantial spikes at that time. The external air temperature sensor data was deemed unreliable for use in determining if an improvement was made in relation to thermal energy performance.

Met Éireann, the Irish National Meteorological Service provides daily weather reports for the Finner Automated Weather Station, temperatures are graphed and hourly temperatures points are identified. The appropriate readings for the external temperature were collected and on the hour data points were extracted from the room temperature data, the resulting graphed data appears in figure 5.2 with the average daily and weekly temperatures collected in table 5.1. The variation from week to week is small, 2-3°C, however the influence of this needed to be evaluated.

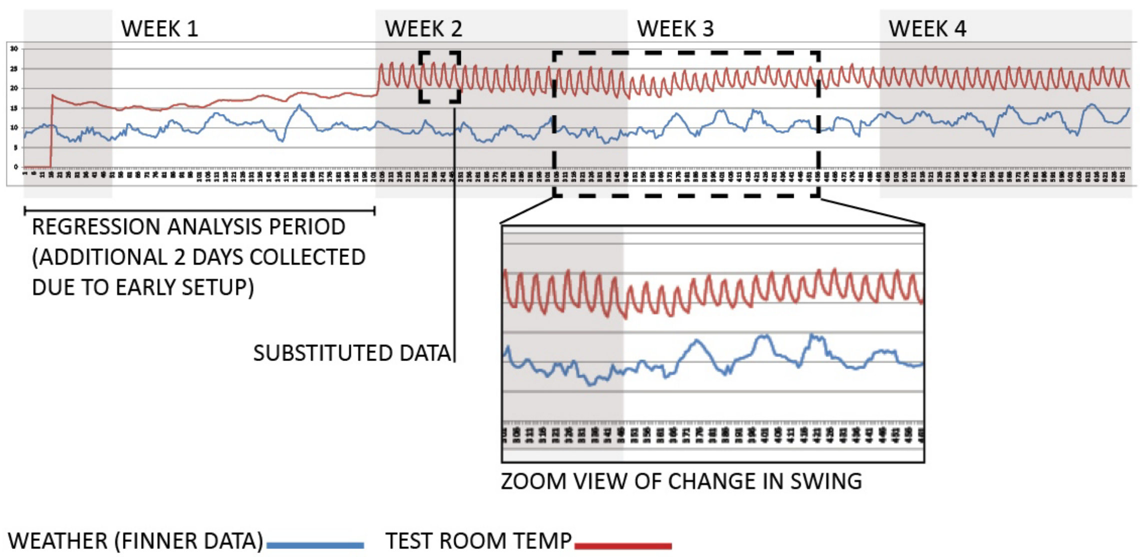


Figure 5.2 External temperature data collected at Finner Automated Weather System and internal temperature readings for test period

Table 5.1

Average Daily and Weekly Temperatures at Finner Automated Weather Station

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Average Week Temp
No intervention	9.1°C	10.2°C	12°C	10.1°C	11.7°C	10.2°C	10.6
Radiator Only	9.6°C	9.4°C	8.3°C	9°C	9.5°C	7.9°C	9
Radiator with MPCM slurry	9.1°C	10.7°C	12°C	10.8°C	10.5°C	11.2°C	10.7
Radiator with Water	12.7°C	12°C	11.7°C	12.6°C	11.9°C	13.1°C	12.3

Note. Data collected by Met Éireann (2015)

Test weeks two, three, and four all showed clear heating and cooling cycles, it appears that despite the slightly colder weather of test week two, the heating cycles reached a higher maximum temperature than those of the following weeks.

5.2 Analysis of Uncontrollable Variables

It was observed that a gradual increase in the room temperature during test week one had occurred when no heating was supplied, leading to an analysis of the known uncontrollable variables, external air temperature and radiator supply pipe heat output. Using SPSS software the researcher ran two regression tests to (1) determine the likely influence of the external temperature on the internal temperature, and (2) determine the possible influence of the pipe temperature on the room temperature.

The regression analysis on the influence of the external temperature on the room temperature can be seen in figure 5.4, it shows a 0.253 R-squared value, indicating that 25% of the change to the interior room temperature was a result of the exterior temperatures.

Descriptive Statistics

	Mean	Std. Deviation	N
ROOM_TEMP	16.6577	1.32169	176
WEATHER	9.9977	1.97669	176

Figure 5.3 Descriptive statistics on the influence of external temperatures on internal room temperature

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.503[a]	.253	.249	1.14553	.253	58.961	1

Figure 5.4 SSPS regression model summary showing the influence of external temperature on internal room temperature

The influence of the pipe which lines the room was also considered as a uncontrollable variable due to its connection to the stove, the main source of heat in the house. The pipe was insulated for the period of the experiment but this would reduce but not prevent heat leaving the pipe and entering the room. The surface temperature of the insulated pipe was monitored for test week one and two, and the data was added to the whole test period graph, see figure 5.5.

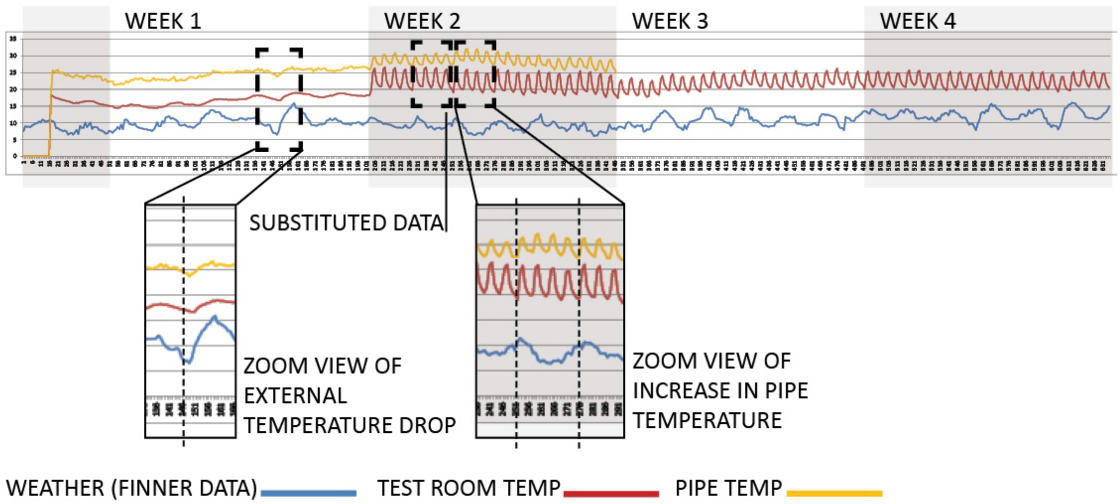


Figure 5.5 External temperature data collected at Finner Automated Weather System, internal temperature readings, and insulated pipe surface temperature data for test period

The pipe temperature data line appears to mimic the external temperature indicating it is influenced by the external temperature. The regression analysis on the influence of the pipe temperature on the room temperature, can be seen in figure 5.7, it has a .702 R-squared value, indicating that 70% of the change to the interior room temperature was a result of the pipe temperature.

Descriptive Statistics

	Mean	Std. Deviation	N
Room_Temp	16.6577	1.32169	176
Pipe_Temp	24.3298	1.46353	176

Figure 5.6 Descriptive statistics on the influence of insulated pipe temperatures on internal room temperature

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.839[a]	.704	.702	.72126	.704	413.640	1

Figure 5.7 SSPS regression model summary showing the influence of the insulated pipe temperatures on internal room temperature

The findings are substantial and must be considered carefully. Stone buildings, such as the test building, change temperature slowly due to their substantial thermal mass, this results in a time delay between the flow of heat from the exterior to the interior. The regression assumes no time delay and no relationship between the pipe temperature and the external temperature which may not be accurate. An Instance identified on figure 5.5 shows an area where the pipe temperature drops along with the room temperature following a drop in external temperature. In this case the drop in room temperature may be deemed by the regression analysis to be caused by the pipe due to the temperature change delay. This may result in inaccurate R-squared values both for the influence of the weather on the room temperature and the pipe on the room.

Having an additional source of heat in the test room is not ideal, the use profile and temperature readings taken elsewhere in the building indicate its influence should not greatly impact the experiment findings. The heat in the pipe is gravity fed from a stove in the kitchen. The building owner leaves the stove on day and night at a low level, if the weather is cold enough to require heating. During the test period the owner was instructed to use the heating as per usual. A maximum minimum thermometer was attached to the surface of a panel radiator fed by the pipe located in the adjoining room. The maximum and minimum temperatures were collected for test week two and test week three but not for test week four as it was rerun at a later date. The temperatures collected are listed in table 5.2. The minimum temperatures never dropped below 19.4^{o}C indicating that during the test period the stove was never switched off. The data also indicates that the pipe temperatures were higher in test week two (radiator only) than in test week three reducing the likelihood that any thermal savings made by the MPCM were caused by the pipe.

Table 5.2

Maximum, Present, and Minimum Temperatures Recorded on Panel Radiator in Adjacent Room

	May 25th – June 1st (Radiator only)	June 1st – June 8st (MPCM slurry)
Max	32.1^{o}C	26.1^{o}C
Present	26.1^{o}C	21.8^{o}C
Min	25^{o}C	19.4^{o}C

Finally, the influence of the pipe would be sensible, heating the room in a gradual and linear fashion, this would change the overall room temperature but not the shape of the cooling slope which is the primary interest of this study.

5.3 Analysis of Internal Temperature Readings for Each Test Week

The reduction of the room temperature swings would increase thermal comfort and could extend the period of heating, which a cycle of heating would provide. This could result in a reduction in energy use and cost for the building heating requirements. The comparison of the weekly data sets for thermometer number 4 (TR) are compared here to visually assess the behavior of the room temperature in response to the change in the independent variable treatment. In figure 5.8 the collected room temperature data sets for test weeks one, two, three, and four are overlaid. Following figure 5.8 the data sets for each test day of each test week were overlaid in figures 5.9 and 5.10 to gain a greater understanding of the individual six hour temperature cycles.

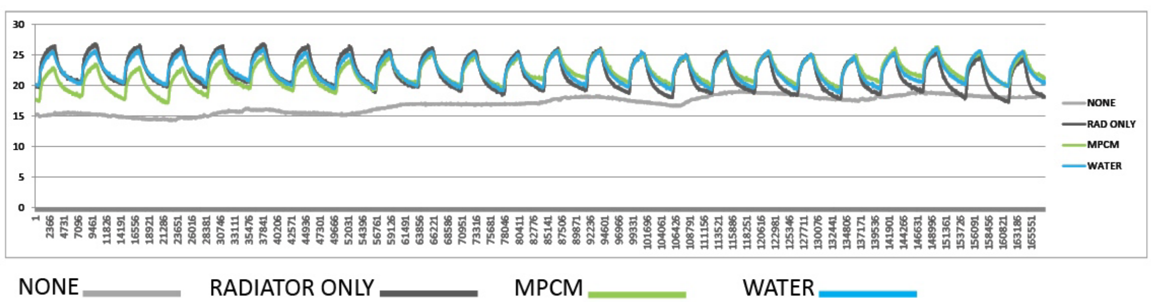


Figure 5.8 Internal temperature data (T4) for each test week overlaid

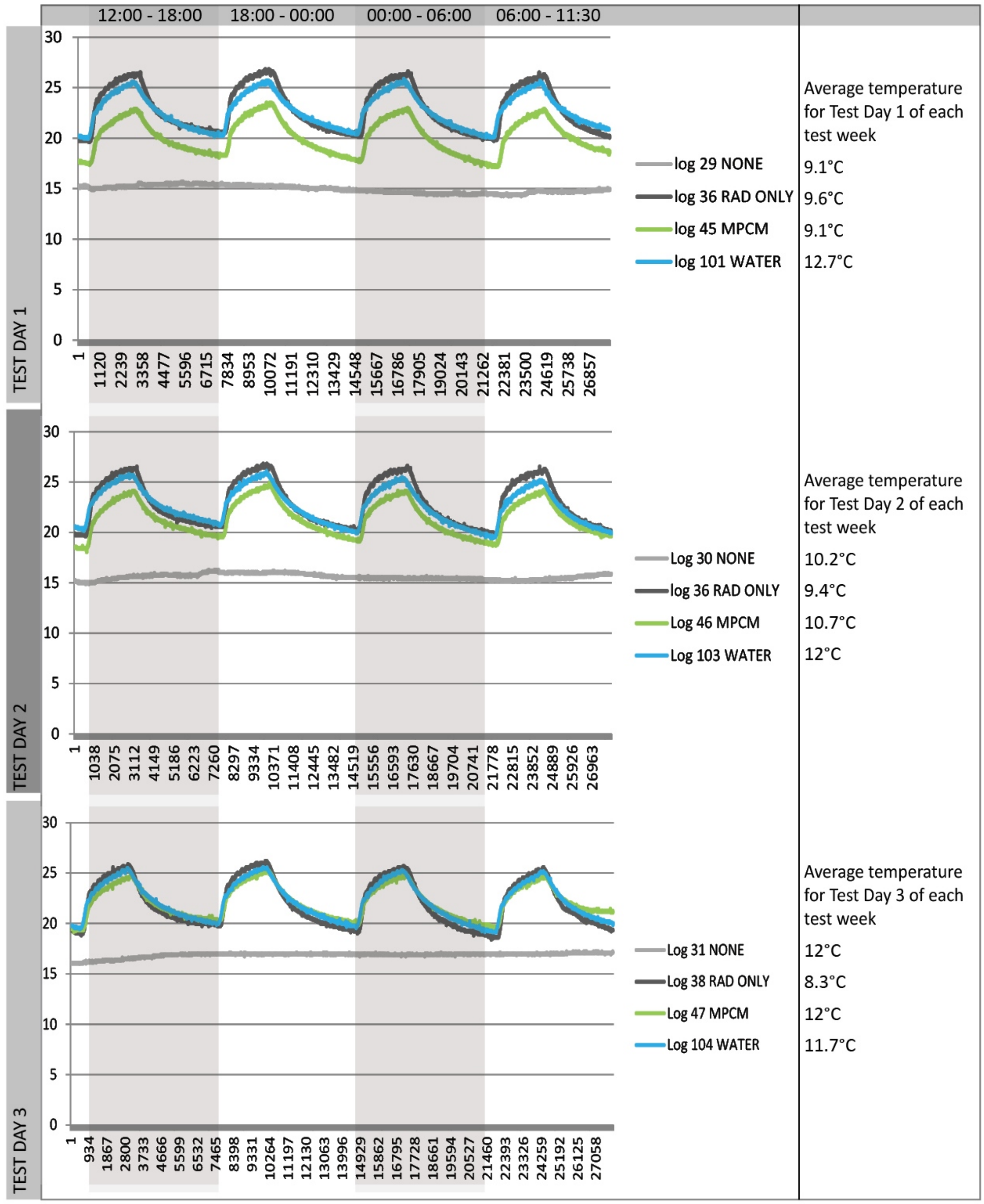


Figure 5.9 Internal temperature data gathered by T4 on the individual test days 1, 2, and 3 of each test week overlaid

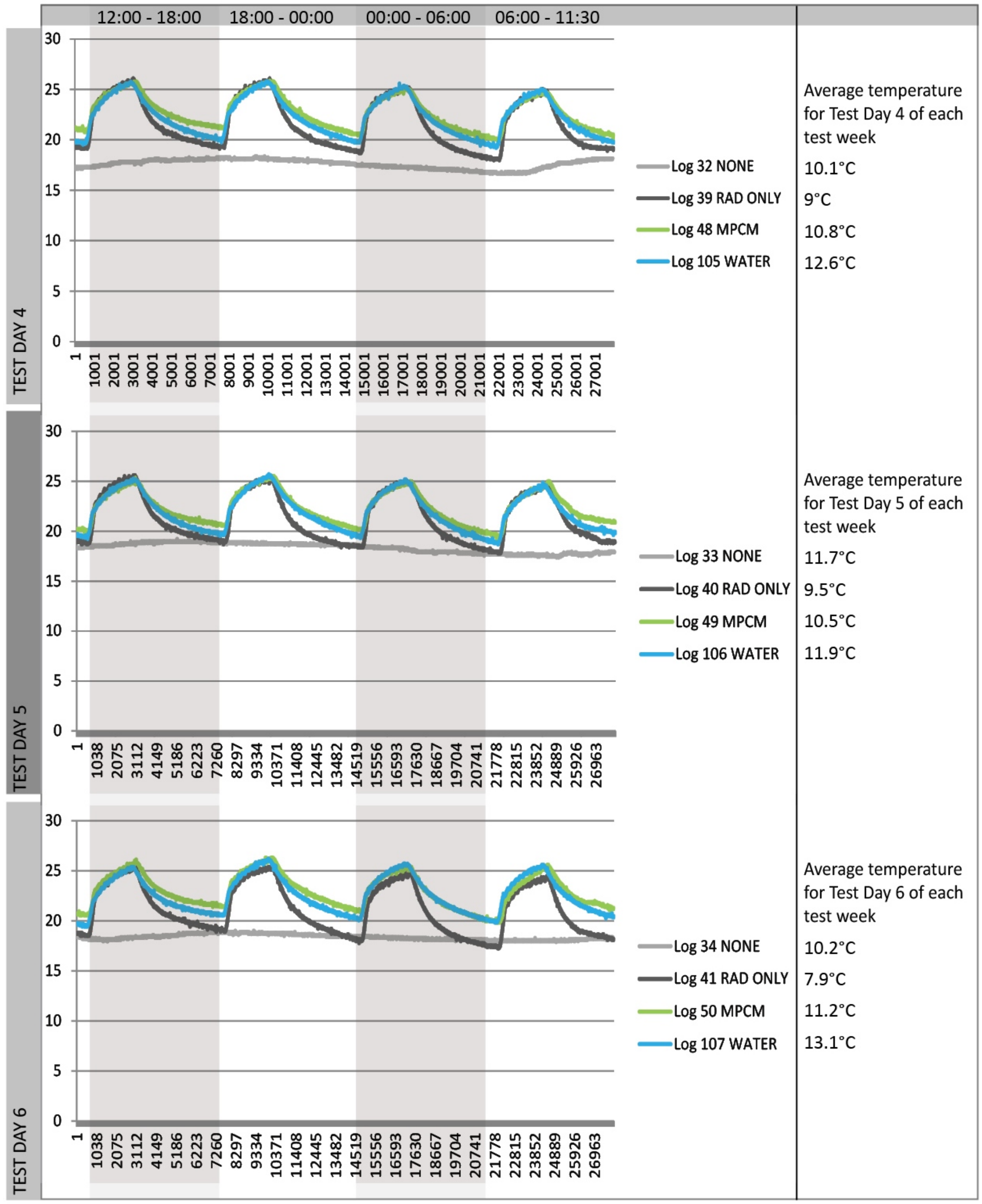


Figure 5.10 Internal temperature data gathered by T4 on the individual test days 4, 5, and 6 of each test week overlaid

5.3.1 Test Week 1

The room temperature Test Week 1 (no heating), appears to average at 15^{o}C for test day one and two, 17^{o}C for test days three and four, and 18^{o}C for test days five and six. These temperatures are low for the majority of building types and heating would be required. Test Week 1 with no radiator shows level readings where temperature changes are slow and minimal. A slight dip can be seen during night time hours followed by a gentle rise during the day.

5.3.2 Test Week 2

The room temperature Test Week 2 (radiator only), shows a consistent heating and cooling profile, max peak temperatures appear to have an average peak maximum temperature of 26^{o}C while the lows appear to fall to a region between 17^{o}C and 19^{o}C before the heating switched on again as scheduled.

5.3.3 Test Week 3

During Test Week 3 (MPCM), the heating and cooling cycles of the MPCM slurry appear to improve as the week progresses. On test day one the room temperature does not go above 23^{o}C which is the lowest peak reading for the test period. Test day two of the MPCM slurry shows an increase in peak cycle temperatures, mimicking the peak cycle temperatures of the other materials. This rate of increase can be seen to reduce from test day three onwards. The researcher hypothesized that the MPCM may be charging, absorbing heat but not releasing it, or the pipe supplying the radiator may have been at a very low temperature at the beginning of this test week, or the pipe supplying the radiator may have been at a very low temperature at the beginning of this test week.

5.3.4 Test Week 4

The data set for Test Week 4 (water), showed very clear heating and cooling cycles, although on average this week was $3^{o}C$ warmer than test week two when there was only a radiator. The room temperature peaks are notably not higher than those of the radiator only test week, supporting the assessment that the external temperature does not heavily influence the internal temperatures. The water appears to have a less steep cooling curve than that of the radiator only cooling curve, it appears to be quite similar to that of the MPCM data.

5.4 Cooling Curve

Considering the six graphs, in figure 5.9 and 5.10, the researcher observed a difference in the shape of the cooling curve of the radiator only test days when compared to the cooling curves of the MPCM slurry and water augmented heating systems. The primary interest of the thesis is to reduce the temperature swings that occur in the heating of historical buildings. Limiting these swings reduces the number of times the heating needs to be turned on and increases the thermal comfort of the occupants. Figure 5.11 shows the 12pm to 6pm, six hour cycle for each treatment on test day five, a clear difference can be seen between the cooling curve of the radiator only treatment and the MPCM slurry and water system treatments.

The heating and cooling cycles of each test week have been graphed together and can be seen in Figure 5.12. Although the maximum and minimum temperatures may vary, particularly in relation to the MPCM, the heating and cooling profiles are consistent. This fundamental change in the cooling curve is of particular interest as it determines the rate at which the room cools. The graphs suggest that the cooling profile for the MPCM and water is consistently less steep than that of the radiator alone.

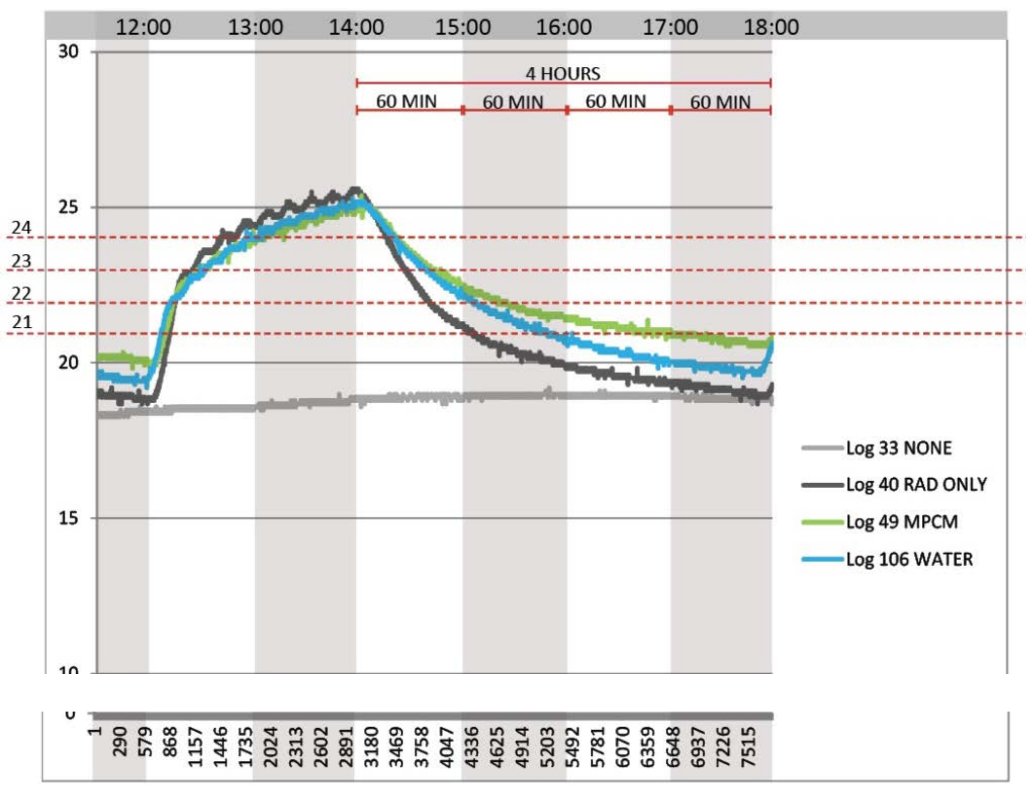


Figure 5.11 12:00 - 18:00 heating and cooling cycle for test day 5 of each week showing variation in cooling profile shape

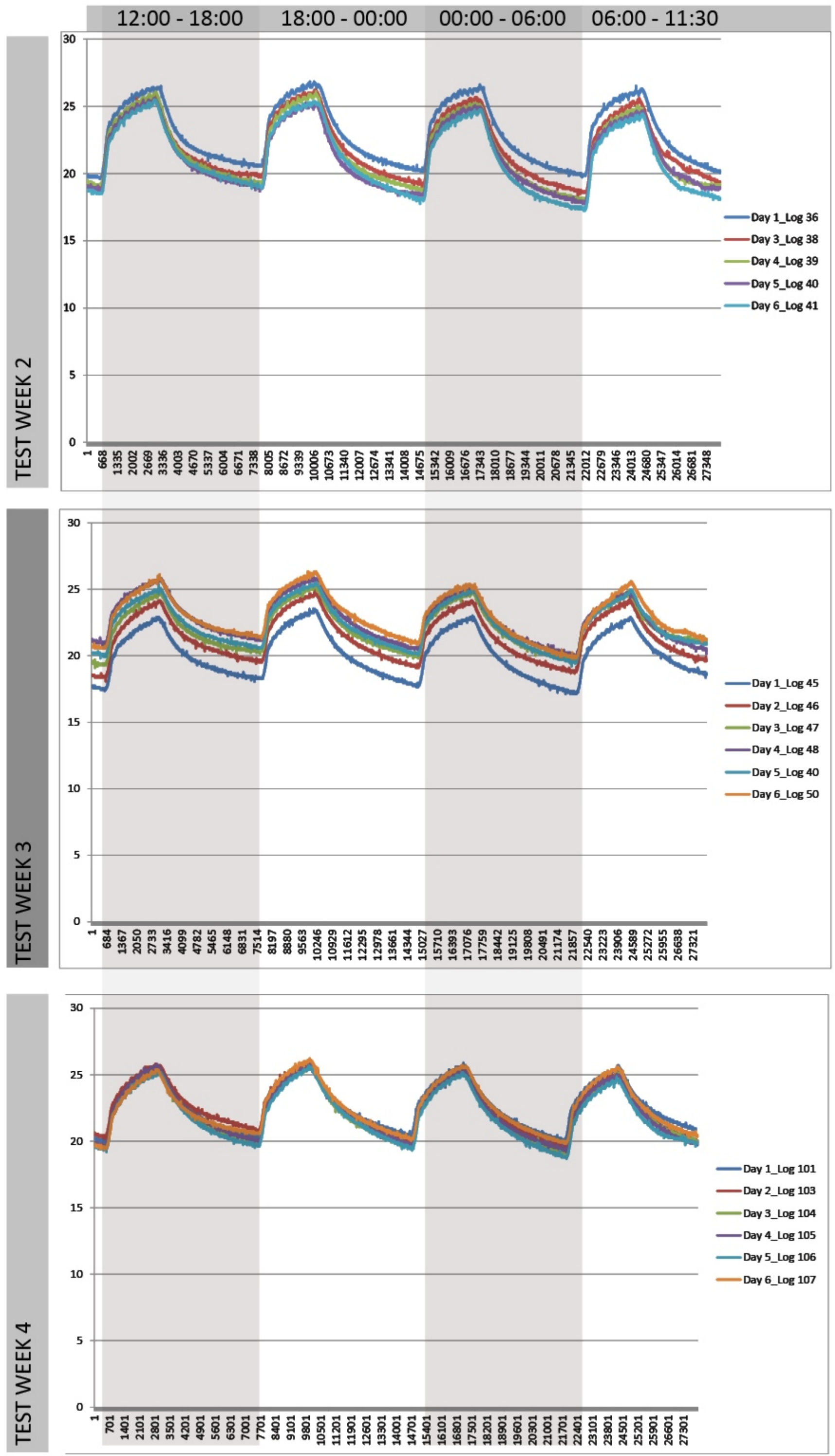


Figure 5.12 All heating and cooling cycles for test weeks 2, 3, and 4 showing consistent variation in cooling profile shape

5.5 Statistical Support of Observed Reduction in Temperature Swings

In order to confirm the visual observations made on the graphed data, descriptive statistical analysis was prepared using SPSS software. The data showed a similar mean for Test Week 2, 3, and 4. It also showed that there was a reduction in the standard deviation between Test Week 2 and Test Weeks 3, and 4, indicating a reduced temperature swing. The descriptive statistics can be seen in figure 5.13, and figure 5.14 shows a box plot of the distribution of the collected data. Histograms and stem and leaf plots show the distribution of the numerical data in figures 5.15, and 5.16 and 5.17 respectively.

		NONE	RAD_ONLY	MPCM	WATER
N	Valid	167662	167794	167806	167853
	Missing	191	59	47	0
Mean		16.9489	22.0095	21.9657	22.4028
Std. Error of Mean		.00330	.00600	.00470	.00453
Median		17.0300	21.4700	21.7800	22.1900
Mode		16.93	19.20	21.26	20.44
Std. Deviation		1.35015	2.45842	1.92411	1.85789
Variance		1.823	6.044	3.702	3.452
Skewness		-.294	.185	-.047	.153
Std. Error of Skewness		.006	.006	.006	.006
Kurtosis		-1.227	-1.266	-.689	-1.274
Std. Error of Kurtosis		.012	.012	.012	.012
Range		4.96	9.60	9.19	7.54
Minimum		14.24	17.24	17.13	18.68
Maximum		19.20	26.84	26.32	26.22
Sum		2841684.79	3693054.79	3685968.52	3760375.43
Percentiles	95	18.7900	25.9100	24.9800	25.2900

Figure 5.13 Descriptive statistics on Test Week 1, 2, 3, and 4 datasets

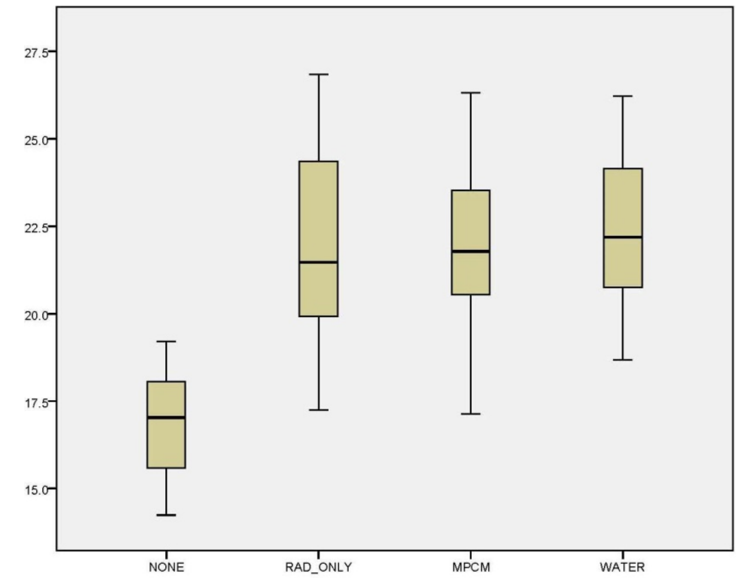


Figure 5.14 Box plot showing distribution of collected data

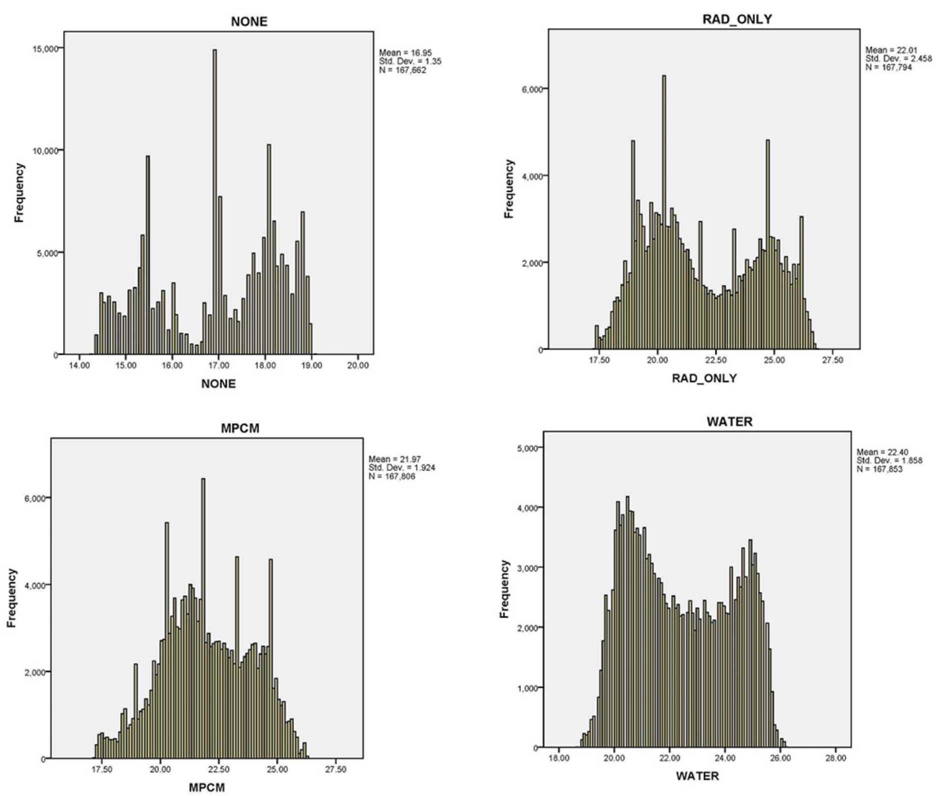


Figure 5.15 Histograms showing the distribution of the numerical data collected during each test week

NONE

```
NONE Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

   950.00       14 .  333333&
  5553.00       14 .  444444444444444445555555555555555
  5382.00       14 .  66666666666666666777777777777777
  3866.00       14 .  88888888888889999999999
  6382.00       15 .  00000000000000000000111111111111111111
 10049.00       15 .  222222222222222222222222223333333333333333333333333333333333
 11922.00       15 .  44444444444444444444444444444444444444444444444444444444445555555555555
  5667.00       15 .  6666666666666666677777777777777777
  1185.00       15 .  9999999
  5427.00       16 .  000000000000000000001111111111111
  1987.00       16 .  222222333333
   944.00       16 .  444555
  3125.00       16 .  6666777777777777777
 16816.00       16 .  8888888888889999999999999999999999999999999999999999999999999999999999999999999999999999999999999999
 10580.00       17 .  000000000000000000000000000000000000000000000011111111111111111
  3932.00       17 .  222222222222333333333333
  4332.00       17 .  44444444444555555555555555
  8823.00       17 .  66666666666666666666666777777777777777777777777777777
  9687.00       17 .  8888888888888888888888888999999999999999999999999999999999
 16766.00       18 .  0000000000000000000000000000000000000000000000000000000000000111111111111111111111111111111111111111
  9213.00       18 .  2222222222222222222222222223333333333333333333333333333
  7291.00       18 .  44444444444444444444444444555555555555555555
 12489.00       18 .  666666666666666666666666666666666677777777777777777777777777777777777777777
  5290.00       18 .  88888888888888888888888899999999
     3.00       19 .  &
     1.00       19 .  &

 Stem width:      1.00
 Each leaf:     167 case(s)


 & denotes fractional leaves.
```

RAD_ONLY

```
RAD_ONLY Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

   543.00       17 .  344&
  1752.00       17 .  55677888999
  5605.00       18 .  0000001111122222222233333334444444444
 10110.00       18 .  55555555555555666666666677777777778888888888888888899999999999999
 11840.00       19 .  1111111111111111222222222222222222222233333333333333333333444444444444444444
 13660.00       19 .  5555555555555555666666666666677777777777777777777888888888888888888899999999999999999999
 15085.00       20 .  00000000000000000000011111111111111111112222222222222222222222223333333333333333333444444444444444
 14601.00       20 .  55555555555555555556666666666666666666677777777777777777777888888888888888888889999999999999999
 10868.00       21 .  00000000000000001111111111111122222222222222223333333333333344444444444
  7609.00       21 .  55555555555566666666666777777788888888888999999999
  5299.00       22 .  0000000001111111333333333344444444
  6430.00       22 .  555555556666666667777777788888888899999999
  6655.00       23 .  0000000001111111222222222233333333344444444
  8906.00       23 .  555555555556666666666677777777778888888888888899999999999
 10780.00       24 .  0000000000000111111111111222222222222222333333333333333344444444444444
 12215.00       24 .  55555555555555556666666666666777777777777778888888888888888888899999999999999999
  8539.00       25 .  00000000000000011111111111111112222222222222233333333333
  8960.00       25 .  5555555555555566666666666677777777778888888888888999999999
  7011.00       26 .  0000000000000111111111222222222233333333444444
  1194.00       26 .  55556667&

 Stem width:      1.00
 Each leaf:     154 case(s)


 & denotes fractional leaves.
```

Figure 5.16 Stem and leaf plot showing the distribution of the numerical data for Test Week 1 (no heating) and Test Week 2 (radiator only)

MPCM

```
MPCM Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

    872.00       17 .  22344&
   2389.00       17 .  555667778899
   3603.00       18 .  0011222233333444444
   4548.00       18 .  555566667777888888999999
   4491.00       19 .  11111222222333333444444
   9117.00       19 .  555556666666667777777777777888888888899999999999
  13738.00       20 .  000000000000001111111111111122222222222222333333333333333444444444444444
  16596.00       20 .  555555555555555555666666666666666666677777777777777777888888888888888899999999999999999
  18502.00       21 .  0000000000000000000111111111111111111122222222222222222223333333333333333333344444444444444444444
  15903.00       21 .  555555555555555555666666666666666666677777777777777777778888888888888888999999999999
  10768.00       22 .  00000000000000111111111111113333333333333344444444444444
  12687.00       22 .  5555555555555556666666666666777777777777788888888888889999999999999
  11397.00       23 .  000000000000011111111111122222222222233333333333344444444444
  12075.00       23 .  555555555555666666666666777777777777788888888888889999999999999
  12104.00       24 .  0000000000000111111111112222222222222333333333333334444444444444
  10594.00       24 .  55555555555555666666666666777777777778888888889999999999
   4705.00       25 .  000000011111122222223333
   2971.00       25 .  555666667778889
    602.00       26 .  012&

 Stem width:      1.00
 Each leaf:     189 case(s)


 & denotes fractional leaves.
```

WATER

```
WATER Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

    554.00       18 .  789&
   2065.00       19 .  1223334444
  10492.00       19 .  55555556666666667777777777777888888888888999999999999
  19296.00       20 .  00000000000000000011111111111111111111222222222222222222223333333333333333333344444444444444444444
  18593.00       20 .  55555555555555555555666666666666666666666777777777777777777888888888888888888889999999999999999999
  15969.00       21 .  0000000000000000000111111111111111222222222222222222333333333333333334444444444444
  12812.00       21 .  55555555555555666666666666667777777777777888888888888899999999999
   9402.00       22 .  000000000000011111111111133333333333344444444444
  11077.00       22 .  5555555555566666666666777777777777888888888889999999999
  11333.00       23 .  000000000000111111111112222222222222333333333334444444444
  11357.00       23 .  5555555555566666666666677777777777788888888888899999999999
  12750.00       24 .  00000000000111111111112222222222222233333333333333344444444444444
  15320.00       24 .  555555555555555566666666666666667777777777777888888888888888889999999999999999
  11130.00       25 .  00000000000000000111111111111111222222222222233333333333
   5279.00       25 .  55555555556666666677777889
    233.00       26 .  0&

 Stem width:      1.00
 Each leaf:     197 case(s)


 & denotes fractional leaves.
```

Figure 5.17 Stem and leaf plot showing the distribution of the numerical data for Test Week 3 (radiator and MPCM) and Test Week 4 (radiator and water)

5.6 Secondary Findings

The behavior of the test liquids in the cans showed evidence of latent heat temperature changes in the MPCM slurry. Though the overall heating and cooling cycles for the MPCM slurry and water appear very similar, see figure 5.18, the data can be seen to 'kink' at approximately 32^{o}C, when examined closer as seen in figure 5.19. Despite the warmer weather of the water test week the MPCM cans sustain a higher temperature overall. The researcher had considered the MPCM to be in a charging period but there the can heating and cooling cycles for Test Day 1 of Test Week 3 do not show a reduced surface temperature in line with the reduced room temperature.

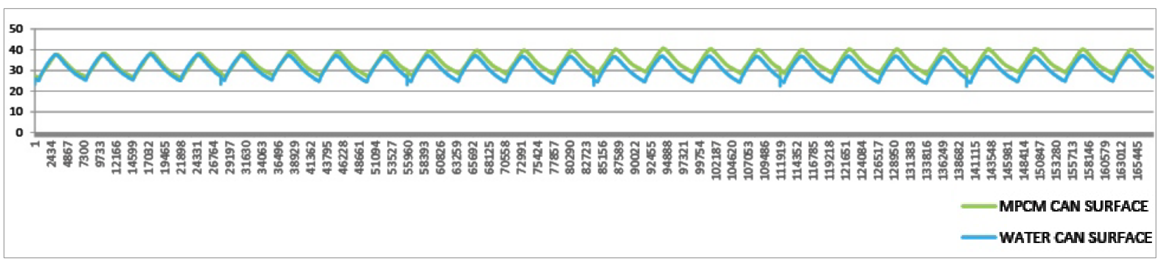


Figure 5.18 Can surface temperature data for Test Week 3 (radiator with MPCM) and Test Week 4 (radiator with water)

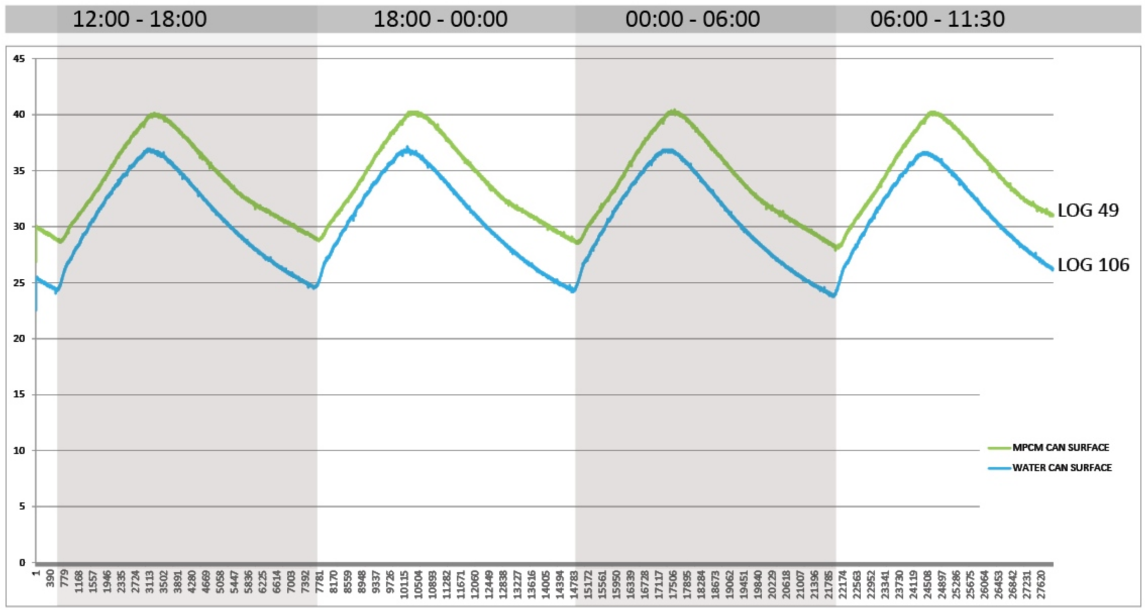


Figure 5.19 Can surface temperature data for Test Day 5 of Test Week 3 (radiator with MPCM) and Test Day 5 of Test Week 4 (radiator with water) showing differences in cooling cycle profile

5.7 Cooling Curve Comparison Using a Large Data Set

The potential financial benefit of the observed augmented cooling curve can be investigated by mimicking the action of a thermostat, this can be done by removing all temperature data below a certain threshold to 'turn on' the heating when the temperature drops to that level. Figure 5.20 shows the overlaid weekly data displayed using a mimicked thermostat setting of 19^{o}C, 20^{o}C, 21^{o}C, and 22^{o}C. These temperatures were chosen to show the behavior of each system at different temperatures. The data sets contain 24 heating-cooling cycles each, and the frequency of times the heating is 'switched on' by the thermostat increases as the room temperature required increases.

It appears that the water provides the best results in all temperatures, followed by the MPCM slurry, and then the radiator on its own. This is not trustworthy as there are two issues with the data; 1) the substituted day two of the Test Week 2 data, and 2) the suspected charging period of the MPCM slurry or substantially low radiator supply pipe temperature. Despite these issues the graphs indicate a reduction in the number of cooling cycles required to heat the room to a constant temperature using MPCM slurry and water over radiator alone, which has positive implications for cost savings. Further more selective analysis was deemed necessary.

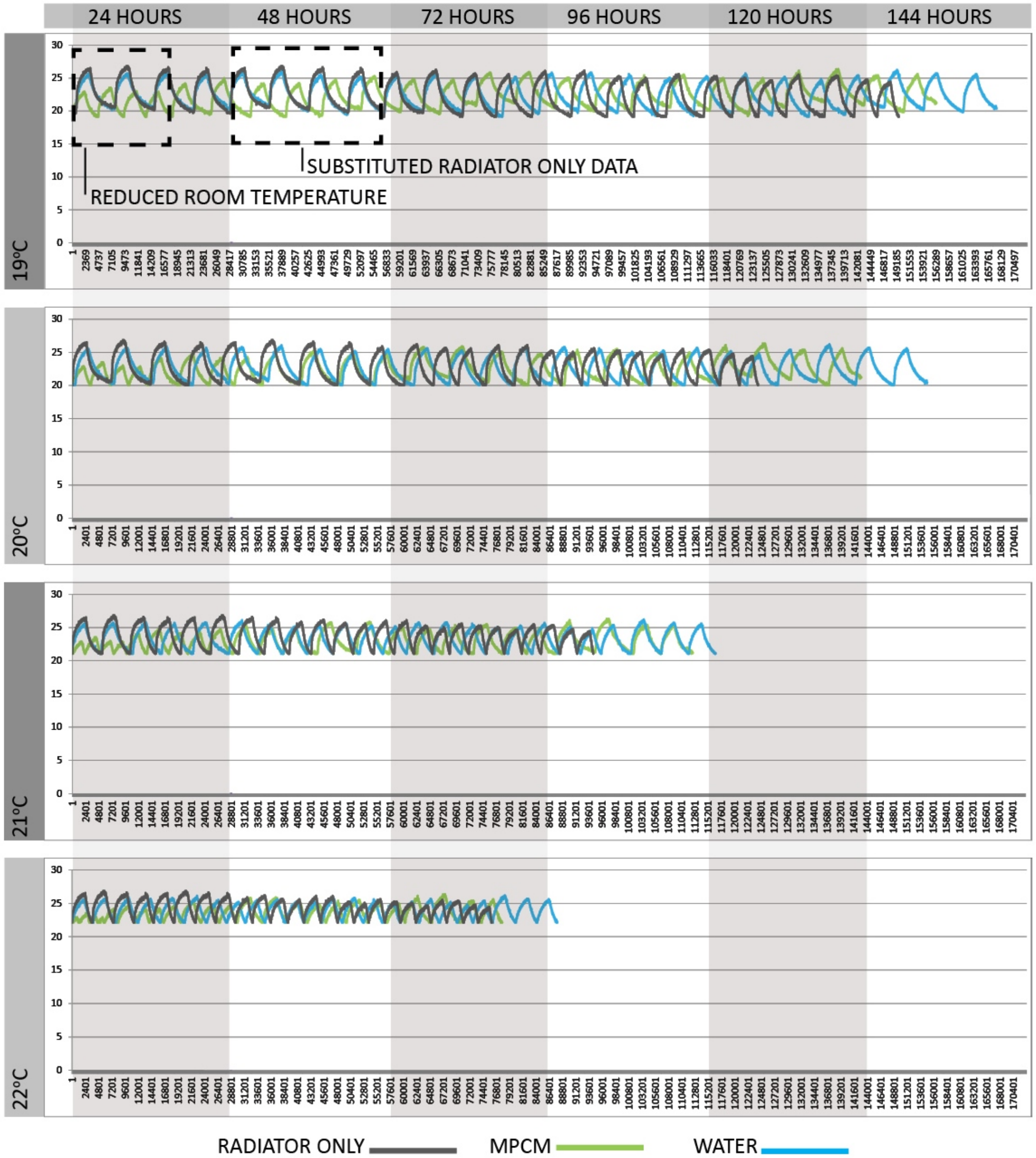


Figure 5.20 Test Week 2, 3 and 4 internal data overlaid showing the 24 2 hour cycles at a thermostat setting of 19°C, 20°C, 21°C, and 22°C. Reduced room temperature due to a possible charging period for the MPCM or a particularly low heat output from the radiator supply pipe, and the substituted radiator data make this an unreliable assessment

5.8 Cooling Curve Comparison Using a Small Data Set

Of the six sets of compared test days, test day 5 showing the heating cooling cycles of each treatment was chosen for further visual analysis. This day was chosen due to the apparent stabilization of the materials and room temperatures. The average temperatures on test day five were 11.7^{o}C for test week one, 9.5^{o}C for test week two, 10.5^{o}C for test week three, and 11.9^{o}C for test week four. Test day six was considered unsuitable due to the cooler external temperature of 7.9^{o}C for the radiator only treatment.

Figures 5.21 and 5.22 shows a repeat of the mimicked thermostat approach, shows the heating cycles required to maintain the room at 19^{o}C, 20^{o}C, 21^{o}C, and 22^{o}C during a twenty four hour period. A twenty-four hour period was used to allow for the accumulation of change over time to become clearly identifiable. The Town Hall Sligo does not operate on a twenty-four hour schedule but many historic buildings do, such as residential homes, hospices, and domestic houses. The number of cycles required to maintain the set temperature are listed in table 5.3.

Table 5.4 shows the percentage reduction in number of cycles required to heat the test room using MPCM slurry compared to a radiator only system for that period. The cycle analysis indicates that the MPCM reduced the number of cycles most substantially at a minimum temperature of 20^{o}C and 21^{o}C, when compared to the radiator only system. The percentage reduction reduced at 19^{o}C and 22^{o}C, this may indicate the latent heat slowed the cooling of the room at temperatures 20^{o}C and 21^{o}C.

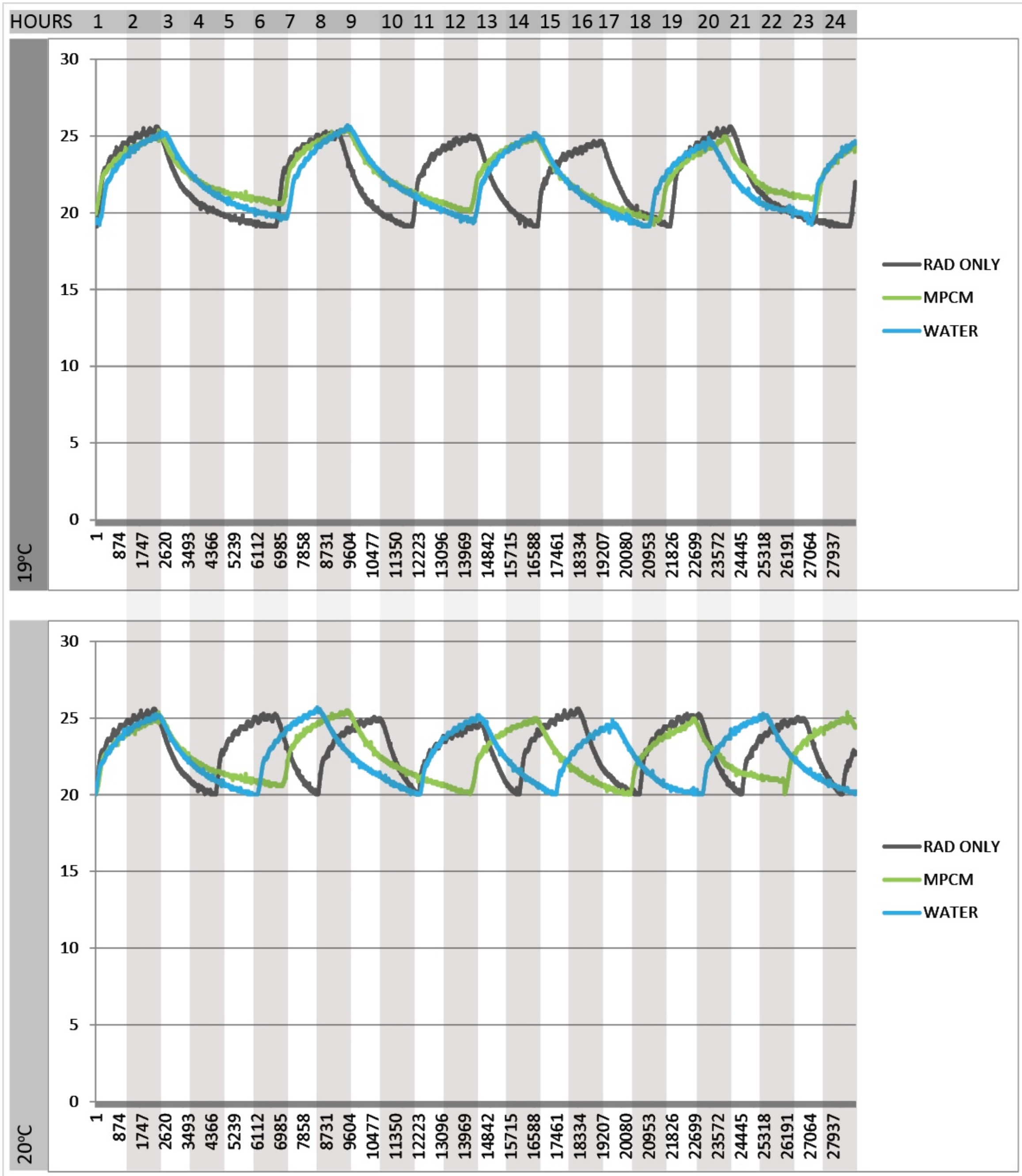


Figure 5.21 Day 5 of Test Week 2, 3 and 4 are overlaid showing the number of 2 hour cycles required in 24hours at a minimum temperature of 19^{o}C, and 20^{o}C

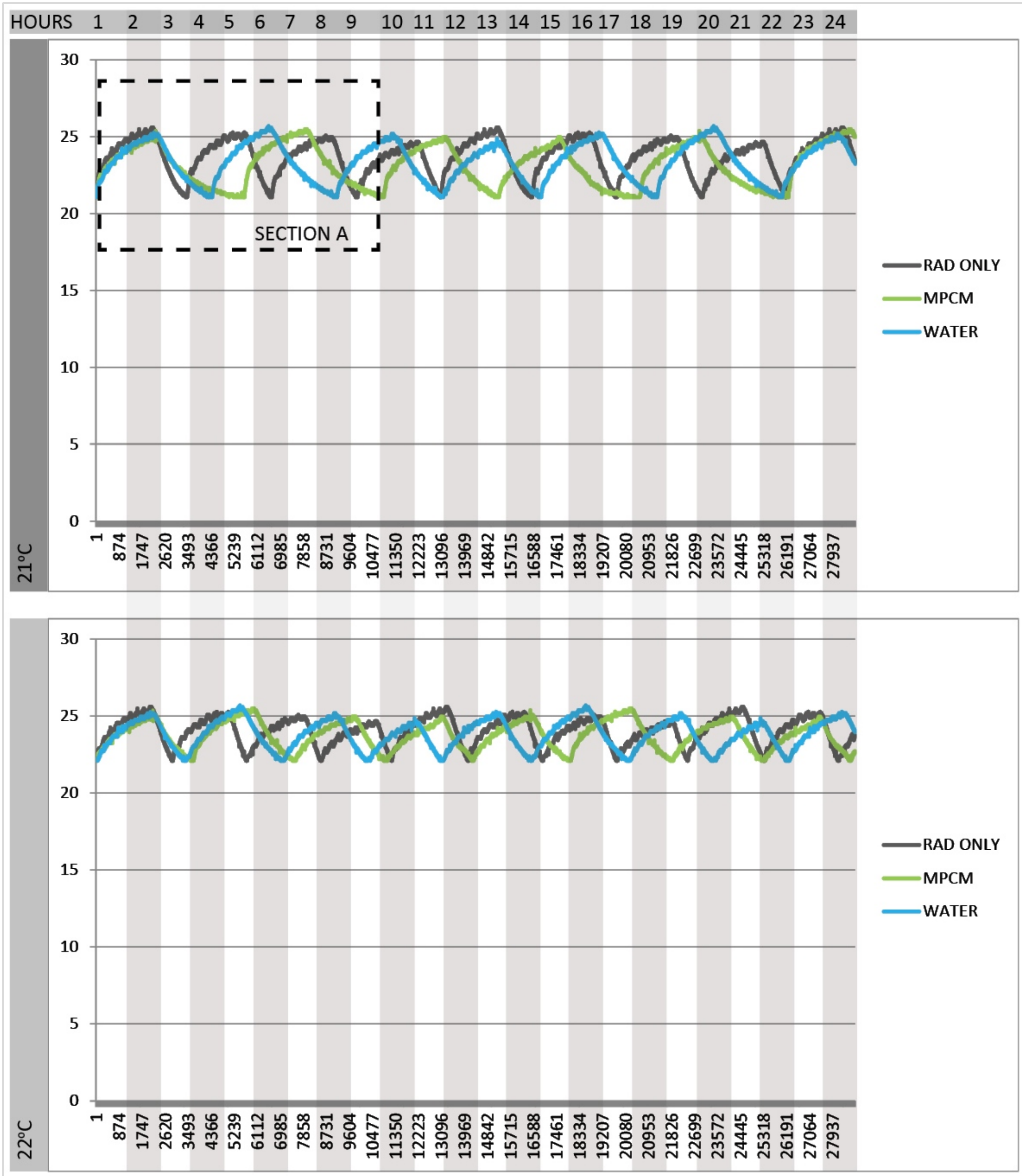


Figure 5.22 Day 5 of Test Week 2, 3 and 4 are overlaid showing the number of 2 hour cycles required in 24hours at a minimum temperature of 21°C, and 22°C

Table 5.3

Number of Cycles Required to Maintain the Room Temperature above a Minimum Set Temperature

	Radiator Only	MPCM Slurry	WATER
19^{o}C	5.1 cycles	4.3 cycles	4.3 cycles
20^{o}C	7.1 cycles	4.5 cycles	5 cycles
21^{o}C	8.7 cycles	5.5 cycles	6.7 cycles
22^{o}C	10.2 cycles	8.1 cycles	8.7

Table 5.4

Change in Number of Cycles (Δ) Required Expressed as a Percentage

	MPCM slurry augmented system compared to radiator only system		MPCM slurry augmented system compared to water augmented system	
^{o}C	Δ in cycle no.	% reduction	Δ in cycle no.	% reduction
19^{o}C	-0.8	16%	0	0
20^{o}C	-2.6	37%	-0.5	10%
21^{o}C	-3.2	37%	-1.2	18%
22^{o}C	-2.1	21%	-0.6	7%

Note. Percentage reduction calculated using the formula: percentage reduction = (Difference in values/radiator value)100

Using the number of cycles required to heat the test room to above the minimum set temperatures of 19^{o}C, 20^{o}C, 21^{o}C, and 22^{o}C, the amount of energy used and associated cost were calculated for kerosene, natural gas, and electricity. Table 5.5 shows the heat loss in watts for the test room at 19^{o}C, 20^{o}C, 21^{o}C, and 22^{o}C, at an external temperature of 10^{o}C. It also shows the amount of energy used in a two hour heating period at each temperature expressed in kilowatt hours. The cost per kilowatt hour or cycle is then calculated for kerosene, natural gas, and electricity.

The costs per unit are based on July 1st, 2015 energy costs compiled by Sustainable Energy Authority Ireland (2015). The cost per cycle for each form of energy at the different set temperatures was then used with the numbers of cycles noted in table 5.3 to estimate the cost over a twenty-four hour period of continuous heating for each of the three active heating systems tested, table 5.8 shows the calculated values of Kerosene, table 5.9 shows natural gas, and table 5.8 shows electricity. The fourth system was removed due to its lack of a heating element. As Sligo does not have a gas supply and the primary source of heating in the region is home heating oil, the cost for the maintenance of a set temperature, twenty-four hours a day over a 365 day year was calculated for Kerosene only, the figures can be seen in table 5.9.

Considering the MPCM in relation to the radiator only, at 19^{o}C the figures show, an annual saving of €20 by the MPCM slurry, at 20^{o}C there was a saving of €67, at 21^{o}C the saving was €90, and at 22^{o}C the saving was €63. The water augmented heating system also resulted in saving over the radiator only, at 19^{o}C there was a saving of €20, at 20^{o}C the saving was €54, at 21^{o}C the saving was €56, and at 22^{o}C it was €45. It should be noted that these figures are based on the heat loss calculations for the 5.67sqm test room at Rossinver, Co. Leitrim, Ireland.

Table 5.5

Cost in Cents of One Heating Cycle for Kerosene, Natural Gas, and Electricity at a Minimum Temperature of 19°C, 20°C, 21°C, and 22°C Inside, with an External Temperature of 10°C*.*

	Heat Loss (W)	2hrs heating kWh	Kerosene Cost per cycle (8 cent/kWh)	Natural gas Cost per cycle (6.74 cent/kWh)	Electricity Cost per cycle (18.24 cent/kWh)
19°C	402.39	0.80478kWh	6.44cent	5.42 cent	14.68 cent
20°C	443.49	0.88698kWh	7.1cent	5.98 cent	16.18 cent
21°C	484.57	0.96914kWh	7.75cent	6.53 cent	17.68 cent
22°C	519	1.038kWh	8.304cent	7 cent	18.93 cent

Note. Fuel Prices from the Sustainable Energy Authority of Ireland (2015)

Table 5.6

Cost in Cents to heat the Test Room Using Kerosene Heating Oil to a Minimum set Temperature of 21°C for a 24hr Period Using: (1) a Radiator Only, (2) Radiator with MPCM, and (3) a Radiator with Water

		Radiator Only		MPCM Slurry		WATER	
°C	Cost per cycle	Cycle	Cost in cent 24hr period	Cycle	Cost in cent 24hr period	Cycle	Cost in cent 24hr period
19°C	6.44cent	5.1	32.84	4.3	27.52	4.3	27.52
20°C	7.1cent	7.1	50.41	4.5	31.95	5	35.5
21°C	7.75cent	8.7	67.43	5.5	42.63	6.7	51.93
22°C	8.304cent	10.2	84.70	8.1	67.26	8.7	72.24

Table 5.7

Cost in Cents to Heat the Test Room Using Natural Gas to a Minimum Set Temperature of 21^oC for a 24hr Period Using: (1) a Radiator Only, (2) Radiator with MPCM, and (3) a Radiator with Water

		Radiator Only		MPCM Slurry		WATER	
^oC	Cost per cycle	Cycle	Cost in cent 24hr period	Cycle	Cost in cent 24hr period	Cycle	Cost in cent 24hr period
19^oC	5.42 cent	5.1	27.64	4.3	23.31	4.3	23.30
20^oC	5.98 cent	7.1	42.46	4.5	26.91	5	29.9
21^oC	6.53 cent	8.7	56.81	5.5	35.92	6.7	43.75
22^oC	6.996 cent	10.2	71.36	8.1	56.67	8.7	60.87

Table 5.8

Cost in Cents to Heat the Test Room Using Electricity to a Minimum Set Temperature of 21^oC for a 24hr Period Using: (1) a Radiator Only, (2) Radiator with MPCM, and (3) a Radiator with Water

		Radiator Only		MPCM Slurry		WATER	
^oC	Cost per cycle	Cycle	Cost in cent 24hr period	Cycle	Cost in cent 24hr period	Cycle	Cost in cent 24hr period
19^oC	14.68 cent	5.1	74.87	4.3	63.12	4.3	63.12
20^oC	16.18 cent	7.1	114.88	4.5	72.81	5	80.9
21^oC	17.68 cent	8.7	153.82	5.5	97.24	6.7	118.46
22^oC	18.93 cent	10.2	193.09	8.1	153.33	8.7	164.69

Table 5.9

Cost in Euro to Heat the Test Room to a Minimum Set Temperature all Year Round when Heating Using Kerosene

^oC	Cost per cycle	Kerosene cost per year (cost per 24hrs x 365)		
		Rad Only	MPCM	Water
19^{o}C	6.44cent	€120	€100	€100
20^{o}C	7.1cent	€184	€117	€130
21^{o}C	7.75cent	€246	€156	€190
22^{o}C	8.304cent	€309	€246	€264

5.9 Analyzing Results with Reference to Sligo Town Hall

Sligo Town Hall is a public building used as municipal offices; it contains individual offices, conference rooms, and office community spaces including a canteen and reception. The heat is switched on at 8.00am and switched off at 4.30pm. Staff use electric heaters to supplement the heating as they perceive a rapid cooling of the building once the heating is switched off. The calculations were based on a twenty-four hour heating use. The Sligo Town Hall heating system operates for 8.5 hours a day. Its office hours are 9-5pm Monday to Friday, the heating is switched on at 8am resulting in a nine hour period where the temperature of building should ideally be in the range of 21^{o}C – 23^{o}C. Table 5.10 is based on a nine hour heating period at a minimum temperature of 21^{o}C, the data is highlighted and labeled Section A in figure *5.22*. The energy used and associated fuel costs are compared for each heating system. The data indicates that the use of MPCM slurry augmented system would save €25 per year when compared to the radiator alone. The water augmented heating system indicated an annual saving of €17 under these conditions. The percentage reduction in number of heating cycles required by the MPCM augmented heating system was 38% when compared to the radiator only system, and 17% when compared to the water augmented heating system.

Calculating the payback period is challenging as the actual quantity of MPCM slurry that contributed to the augmented heating and cooling profile is not known. The additional costs of assembling and insulation of such a system are also unknown. In the case study examined here a simple payback analysis can be done. The total cost of the experimental equipment was €648 for the MPCM slurry augmented system and €103 for the water augmented system, see table 5.11.

The payback period for the MPCM slurry heating system would be 25.92 years, while the water augmented heating system would take 6.06 years. While the payback period for the water is considerably shorter than that of the MPCM slurry system, it is more limited. The PCM could be furthered engineered in terms of its form, temperature, and concentration with increases in efficiencies reducing the overall quantity required, and therefore the cost of the system.

Table 5.10

Cost in Euro to Heat the Test Room to a Minimum of 21^{o}C for One Business Day of 9hrs, and for a Working Year of 8hr Days Using Kerosene, and Based on Section A of Figure 5.22

Heating System	Cycles in Section A	Cost per cycle (1.038 kWh) for Kerosene	Cost per 8 hr. heating day	Cost per year with 260 working days
Radiator Only	3.25	7.75cent	€0.25	€65
MPCM Slurry	2	7.75cent	€0.16	€40
Water	2.4	7.75cent	€0.19	€48

Table 5.11

Payback period calculation based on equipment cost and estimated savings

Component name	MPCM Slurry system component cost	Water system component cost
Cost of test fluid incl. shipping	€545	Negligible
Cans	€22	€22
Bags	€4	€4
Racks	€38	€38
Total	€609	€64
Saving per annum	€25	€17
Payback period	24.36 years	3.76 years

5.10 Observations on Test Apparatus

It was observed by the researcher that there was a separation of the MPCM from the conductive fluid water. The product specifications acknowledged that there may be some separation but that stirring could remedy the issue. The researcher was surprised at how quickly the material separated, seeing the separation after one week of heating cycles, see figure 5.23. No substantial further separation was seen following three months at a cool temperature.

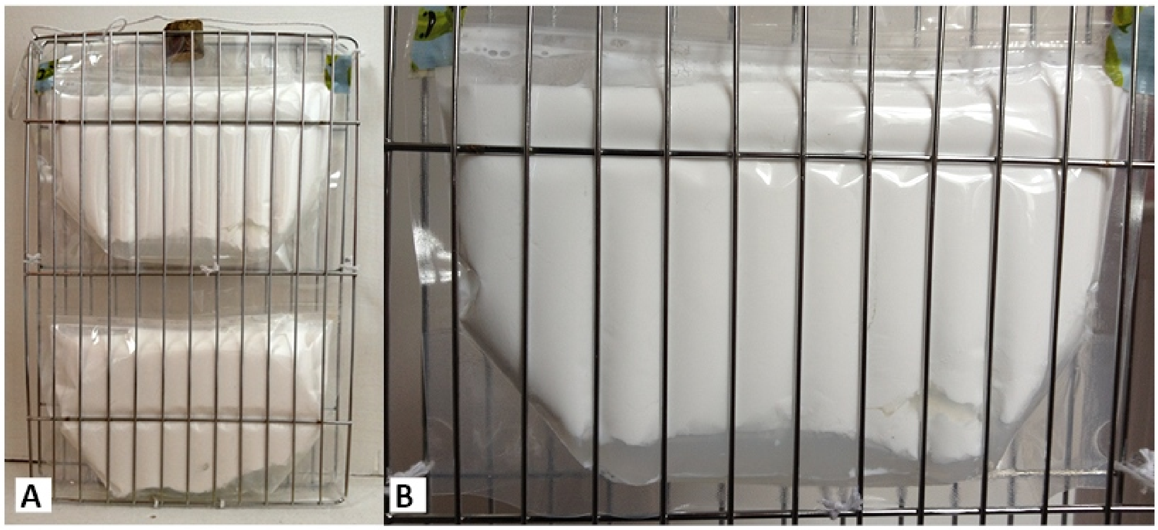


Figure 5.23 Image showing A) MPCM slurry prior to separation, B) MPCM slurry after one week of testing, and C) close up of separation

The distribution of heat in the MPCM slurry was not even during the experimental period. Cans closer to the top were considerable warmer to the touch than those at the bottom. The thermometer was placed on the upper portion of the middle can, while it reached a temperature that would allow for phase change, the eight cans below this level may not have reached a high enough temperature for a long enough period to initiate a phase change.

5.11 Summary

This chapter documented the steps taken to analyze and interpret the collected data. The influence of the uncontrollable variables of external temperature and radiator supply pipe temperature was evaluated and factored into the analysis. The room temperature data was graphed and assessed for changes in its heating and cooling cycles. It was observed that the shape of the heating and cooling had altered and the temperature swings had reduced from Test Week 2 to Test Weeks 3 and 4. Statistical analysis corroborated these visual assessments of the graphed data.

The number of heating cycles required to heat the Test Room for twenty-four hours was evaluated and the associated costs were calculated. Following this the Sligo Town Hall building heating schedule was mimicked and the possible annual savings and payback period were estimated.

Overall the results indicated a reduction in the peak temperatures and a reduction in the speed of cooling with the use of the MPCM slurry augmented heating system.

CHAPTER 6 CONCLUSION

The acknowledgement by nations, academia, and society that we must do more with less in order to reduce the damage to the environment, has opened new avenues for research. The use of phase change materials in construction is an emerging area of innovative technologies and construction materials. This study endeavored to contribute to this exciting field of research and this chapter summarizes the course of the research development, its execution, and its findings.

6.1 Scope and Main Findings

The focus of this study was to establish if the thermal performance of an existing building could be improved with the use of latent heat storage materials. An increase in thermal performance would decrease energy use and increase occupant comfort levels, therby increasing the functionality of existing buildings, protecting their structure and artifacts, and prolonging their lifespan. In this study, Sligo Town Hall provided a focus for the research, built in 1865, this Lombardo Romanesque palazzo style building is a landmark in the town, a dignified piece of civic architecture.

The latent heat storage evaluated in this study was microencapsulated phase change material slurry, an organic wax in small nanometer beads, coated in a layer of polymer and dispersed in water to form a thermal storage liquid.

This evaluation was initially facilitated through the research of relevant literature covering sustainable development, international agreements, legislation, the significance of historic buildings and the challenges associated with their upgrading. Thermal energy storage and the physical composting and behavior of the different kinds of PCM materials were explored and their characteristics analyzed in terms of suitability for the research.

Following the literature review, the methodology for the study was defined. The chosen methodology was a case study approach and the current academic parameters and components of a case study according to experts were discussed. The methodology allowed a framework to be developed to support the study of the research question; can the central heating system of Sligo Town Hall be retrofitted with microencapsulated phase changing material slurry to improve thermal energy performance?, what would be the estimated percentage improvement and payback period?

At the core of the case study was a field experiment, designed to gather ‘real’ world data on how effective the addition of MPCM might be. The components of this experiment were explored with the benefits and challenges of the experimental environment considered and illustrated.

Twenty-six data sets were used for analysis; twenty-four test days and two weather data sets. The data was analyzed visually using graphs and statistically using predictive analytics software. The observations of this initial analysis were then used to assess the potential change in terms of energy consumption and cost provided by the augmented heating system, first, at a general level and at a number of different minimum temperatures, followed by a replication of the Town Hall temperature and heating schedule scenario, examining the possible benefits derived if a room of similar size and structure was located in the town hall.

6.2 Research Methodology

The choice of case study approach was useful in that it allowed for flexibility in the type of data sources used. As the researcher developed their knowledge of MPCM slurry, the research could be adapted to fit a new strategy of data collection and analysis. The case study approach also posed risks to the study as it relied on the researcher’s ability to define the limits of the study, acknowledge and manage any bias, and identify and mitigate threats to validity.

The study of case study methodology provided a structure for the research and defined the parameters for data collection and analysis with regard to the influence of the independent variable, the heating system on the dependent variable, the room temperature.

The site visit to the Sligo Town Hall identified the challenges that can prevent good thermal efficiency, even in a building that has been sensitively renovated using known methods for thermal improvement. Occupant behavior, mechanical faults, and poor design, can reduce energy efficiency and increase costs.

The lack of a suitable test space in Sligo Town Hall resulted in a substitute building being used for the field experiment. The buildings both have solid, thick stone walls, and single glazed windows. While this focuses primarily on the 38,000 protected structures in Ireland, there are thousands of buildings like the test building that are not protected, but have all the heating and moisture related challenges of a notable historic structure.

The test building provided a controllable and accessible environment for the research, however the presence of a heated pipe and the impact of the morning sun on the thermometer were variables that should be avoided in any future research to increase the validity of the results and analysis.

The process for building and testing the field experiment equipment was detailed; the inclusion of the thermometer details, radiator choice, and test fluid container trials was intended to show the rationale behind the final setup and identify strategies that did not work for the benefit of any future research. In particular, reference to the trial fluid containers, parameters such as heat resistance, overall size, volume, cost, and thermal conductivity were considered and resulted in a two part system of twenty-four 500ml cans containing twelve liters of water, and eight sandwich panels made of two 500ml plastic bags between two wire racks, holding a total of eight liters of test fluid.

Thermometers monitored the external air temperature, internal air temperature, can surface temperature, and pipe surface temperature for the duration of the experiment, resulting in daily data logs which could be used to analyze the impact of each heating system on the room temperature.

6.3 The Primary and Secondary Findings

The data logs collected during the field experiment were analyzed using graphs and descriptive statistics. The visual analysis of the data graphs was the primary method of analysis, patterns and anomalies were identified and could be studied further. The descriptive data analysis supported the observations made and provided a more precise understanding of the gathered data.

The primary finding of the data was the reduction in temperature swings. The descriptive statistics showed a reduction in the standard deviation and variance from the radiator only scenario to the MPCM slurry and water systems. The room temperature cooling curve for both the MPCM slurry augmented heating system and the water only augmented system, showed a consistent change in its slope which indicated that the room cooled more slowly and delayed the need to switch on the system again. The standard deviation changed from 2.45842 to 1.92411 and 1.85789 respectively, while the variance reduced from 6.044 to 3.702 and 3.452. The highest recorded mode was during the testing of the MPCM slurry heating system.

The secondary findings show that the can surface temperature behaved differently during Test Week 3 than Test Week 4. It was observed that the can surface temperature would change the rate at which it was slowing down at approximately 32^{o}C. This change indicated the release of heat by the MPCM slurry. Despite the warmer weather of Test Week 4, the MPCM slurry maintained consistently higher can surface temperatures.

The external temperature remained quite low for the duration of the experiment. The thick stone walls reduce the influence of the external temperature, while the single glazed window has a very low thermal resistance. A delayed response in internal temperature was seen in the data and a regression analysis indicated that 25% of the internal change in the internal temperature was caused by the external temperature.

6.4 Problems Encountered and Limitations to the Study

There were a number of practical challenges to the collection of data. These related to the location, the linear rather than simultaneous testing, the temperature monitoring equipment, the test equipment, and the limits of the researcher's knowledge of thermodynamics. It is important to acknowledge these issues so that the results can be understood in terms of its limitations.

The location and linear rather than simultaneous testing aspect concern the morning sunlight, weather, and radiator supply pipe. The experiment had been planned for an earlier part of the year which would have mitigated the issue of the morning sunlight distorting the external temperature readings. The possible influence of the weather and the radiator supply pipe could have been considerably reduced if the experiments had all taken place during the same timeframe and under the same conditions, without interfering with each other. This was not possible due to location restrictions.

The presence of a heated pipe was not ideal as it supplied additional heat to the room that could not be controlled by the researcher. The pipe was insulated and a regression was run on the surface temperature data collected. The regression indicated that 70% of the change in internal temperature during Test Week 1 could be attributed to the pipe. This result was considered and discussed with reference to the external temperature regression and it was noted that a time delay may reduce the amount of data attributed to the weather, and possibly add to the influence of the pipe. The change over the week was quite minimal and the second week of pipe surface readings showed that the pipe temperature mirrored the changes in room temperature caused by the heat of the radiator.

Consideration of the profile of use of the stove by the occupant, and the maximum minimum temperatures gathered on the radiator supplied by the pipe, it was reasoned that it was quite consistent in its supply of heat. While it may increase the temperature overall by a minimal amount, it would not change the shape of the cooling arc which was the primary focus of this study.

The thermometer system was essential in collecting the room data, it allowed several thermometers with a similar standard of error to collect data. It was set to collect data at three second intervals which resulted in a very large quantity of data entries. A lesser time interval would have made the data simpler to analyze.

The monitoring of the test liquids was limited to the surface temperature of one middle position can (thermometer no.1) each week. This followed the damage done to thermometer no. 5, which had originally been collecting the surface temperature of the test liquid bag. More sensors could have been used to understand how the heat was moving, providing greater insight into the effectiveness of the test apparatus design.

Although the researcher endeavored to maximize the relationship between the test fluid and the heat emitted by the radiator, a more efficient system may have ensured greater distribution of heat throughout the MPCM slurry.

Twenty liters of test fluid was used during Test Week 3 and 4, and the percentage of test fluid that influenced the room temperature profiles is unknown. It is possible that only a fraction of the MPCM slurry had a phase change during its heating and cooling cycle as it was observed that the lower cans were cooler to touch than those on top.

MPCM slurry enhanced heating system showed a gradual improvement in its heating as the test week progressed. The researcher reasoned that the PCM was either ‘charging’ due to its low starting temperature or that the radiator supply pipe was at its lowest temperature for that week on that first day, it may also have been both. If the MPCM was solely responsible for the decreased room temperature, then there may be implications in terms of responsiveness for the system. A charging phase after a period of no heating may be problematic.

The separation of the MPCM slurry during Test Week 3 is not ideal. Separation reduces the uniformity of the molarity, possibly inhibiting its ability to absorb and release heat. While the MPCM slurry outperformed the water, there was still an improvement with the water at a lower cost.

Finally the limitations of the researcher's knowledge must be acknowledged. The researcher has a background in architecture and approached this research from a building function perspective rather than a product engineering perspective, decisions made regarding the assembly of the test equipment may not have been best practice by an expert in thermal engineering, although Pat Doyle, Senior Project Engineer at Sligo County Council was consulted on a regular basis.

6.5 Degree to Which the Thesis Question was Answered

The purpose of this study was to investigate; can the central heating system of Sligo Town Hall be retrofitted with microencapsulated phase changing material slurry to improve thermal energy performance?, what would be the estimated percentage improvement and payback period?

The researcher concludes that the research question has been answered. The room temperature data collected during the testing of the MPCM slurry showed a reduction in temperature swings and a slowing of cooling in the test room. This research was then inferred to the Sligo Town Hall; minimum room temperatures and building heating schedules were mimicked, the results of which indicated a reduction in the number of heating cycles required. At 21^{o}C, in a heating period of nine hours, the MPCM only required two heating cycles, or four hours of heating time, while the radiator only scenario required 3.25 cycles of heating, or just over six hours of heating. This change in heating cycle requirements at an internal minimum temperature of 21^{o}C, with an external temperature of 10^{o}C, was 37%. The payback period was estimated using annual savings which were a result of the 37% improvement in thermal performance. The annual cost to heat the test room to a minimum of 21^{o}C at 10^{o}C for a nine hour period each business day was €65 for the radiator only heating system and €40 for the MPCM slurry augmented heating system, this resulted in a €25 saving per business year (260 days). Cost of construction for the MPCM slurry augmented heating system was €648, which results in a 25.92 year payback period.

6.6 Questions Raised as a Results of the Study

Following the analysis of the data a number of questions were raised, primarily:

- How would the results compare if the weather and radiator supply pipe variables were removed?
- How would the room temperature have behaved if the MPCM slurry system had been left on for longer?
- Would a shape stabilized MPCM material be more effective? The issue of separation of the material would be removed.
- Is the use of portable electric heaters in public buildings common? The researcher is aware anecdotally of people using electric heaters in public buildings, sometimes all day, in addition to the central heating system. As staff are not paying the energy bill they may overuse an electric radiator resulting in overheating, energy waste, and additional building running costs.

- Could this strategy improve the thermal energy performance of more recent buildings?

The questions raised open avenues for research to be done on the test material MPCM, the experimental equipment, and the interaction of building users with their thermal environment.

6.7 Recommendations for Further Study

Having considered the literature review, the data collection, and results of the data analysis, the researcher recommends three plans for future study;

1. The experiment should be refined and repeated.
2. The strategies for the implementation of a latent heating system should be explored.
3. The use of personal space heaters in publically funded buildings should be assessed.

To carry out recommendation no.1, the reduction in validity as a result of variables should be dramatically reduced or entirely removed. This could be done in two ways; a) a larger field experiment, or b) a lab experiment. An enlarged field experiment could be done where each heating system is tested simultaneously in four different rooms, with the same dimensions, same occupancy levels, and with the same orientation, such as a school or office block. Issues with the amount of heat released from the existing radiators, the increased equipment required, and possibility of uncontrollable, unknown variables supports the researchers preferred option of 2) a lab experiment. A lab experiment would consist of a temperature controlled space in which the experiment as performed at Rossinver could be repeated to test and corroborate the results of this study. Should the results be validated, the experiment could be run for longer and more detailed consideration could be made of the testing schedule, and the quantity and type of PCM.

Should the data be corroborated, recommendation no.2 is to examine the potential benefit in different building typologies. The application of this technology in different heating strategies could be explored as part of a multifaceted approach as illustrated in figure 6.1.

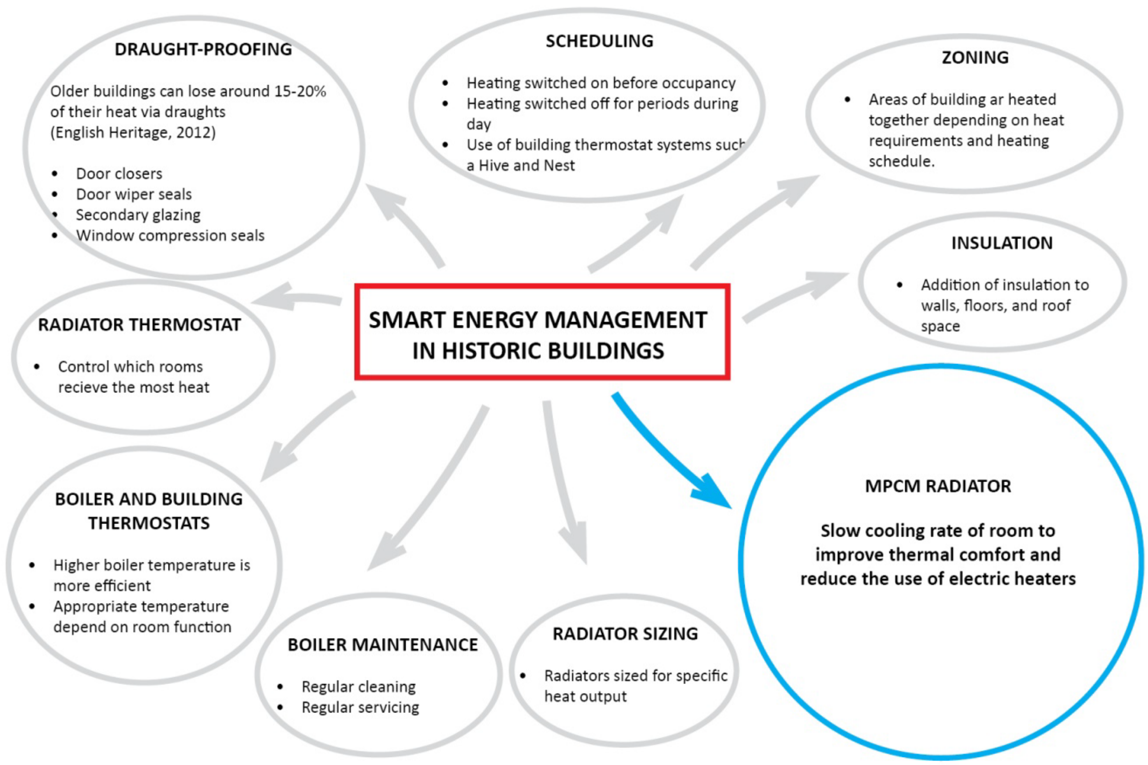


Figure 6.1 Strategies for smart energy management in historic structures

In order to investigate recommendation no. 3; the quantity, size, type, and operation hours should be collected along with the reasons why building occupants use them; do they feel the building is always cold?, is there a draught?, and does it get cold at certain times of the day? Building users should be asked how closely they regulate their personal heater, both for temperature and duration of use. Ideally a survey would show that the use of personal heaters is rare, the alternative would mean that a serious evaluation would need to be made about the management of heat in publicly funded buildings.

6.8 Summary

This chapter summarized the findings and conclusions of the study. The research focus was described along with the impact of the chosen methodology. The findings were summarized and the problems and limitations of the study were discussed. The degree to which the findings when considered along with the study issues and limitations was assessed, with the questions arising from the study listed. Finally, the recommendations for further research were detailed, with three strategies put forward to help further the study of the use of phase change material to improve the thermal energy performance of the national building stock.

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APPENDICES

Appendix A U-value calculations for building structure

Table A.1

U-value of external wall structure

Layer/Surface	Thickness (m)	Conductivity (W/mK) K-Value	Resistance (m^2K/W) R-value
Internal surface	-	-	.12
Wallpaper	.0005	Negligible	Negligible
Plaster (Lime)	.012	.7	.017 [a]
Limestone wall	.5334	1.5	.3556 [a]
Render (Lime)	.012	.7	.017 [a]
External surface	-	-	.06
Total resistance			.5696
U-value			1.7556 $m^2 \cdot K/W$ [b]

Note. U-value calculation formula from Architects Pocket Book (Baden-Powell, Hetreed, and Ross, p154, 1997).

Lime plaster resistance figure from CLEAR (2015)

Thermal conductivity values sourced from Littlefield (2008), Baden-Powell (2003), and Integrated environmental solutions (2015)

[a] Resistance R-value = thickness (m)/ Conductivity (W/mK)
[b] $U = 1/ (R_{SI} + R_{SO} + R_A + R_1 + R_2 + R_3 \ldots\ldots.)$

Where R_{SI} = thermal resistance of internal surface

R_{SO} = thermal resistance of internal surface

R_A = thermal resistance of air spaces within construction

R_1, R_2, R_3, etc. = thermal resistance of successive components

Table A.2

U-value of internal wall

Layer/Surface	Thickness (m)	Conductivity (W/mK)	Resistance (m^2K/W)
Internal surface	-	-	.12
Wallpaper	.0005	Negligible	Negligible
Plasterboard	.01	0.16	.0625 [a]
Cavity	-	-	.18
plasterboard	.01	0.16	.0625 [a]
Wallpaper	.0005	Negligible	Negligible
Internal surface	-	-	.12
Total resistance			.545
U-value			1.83486 $m^2 \cdot K/W$ [b]

Note. U-value calculation formula from Architects Pocket Book (Baden-Powell, Hetreed, and Ross, p154, 1997).

Lime plaster resistance figure from CLEAR (2015)

Thermal conductivity values sourced from Littlefield (2008), Baden-Powell (2003), and Integrated environmental solutions (2015)

[a] Resistance R-value = thickness (m)/ Conductivity (W/mK)
[b] $U = 1/ (R_{SI} + R_{SO} + R_A + R_1 + R_2 + R_3 \ldots\ldots.)$

Where R_{SI} = thermal resistance of internal surface

R_{SO} = thermal resistance of internal surface

R_A = thermal resistance of air spaces within construction

R_1, R_2, R_3, etc. = thermal resistance of successive components

Table A.3

U-value of floor

Layer/Surface	Thickness (m)	Conductivity (W/mK)	Resistance (m^2K/W)
Internal surface (Floor)	-	-	.14
Carpet (simulated sheep wool)	.01	.06	.1667 [a]
Timber floor	.0254	.14	.18 [a]
Cavity	-	-	.18
Ceiling boards	.00635	.14	.04535 [a]
Ceiling tiles (polystyrene)	.0127	.032	.3968 [a]
Internal surface (ceiling)	-	-	.10
Total resistance			1.20885
U-value			. 827 $m^2 \cdot K/W$ [b]

Note. U-value calculation formula from Architects Pocket Book (Baden-Powell, Hetreed, and Ross, p154, 1997).

Lime plaster resistance figure from CLEAR (2015)

Thermal conductivity values sourced from Littlefield (2008), Baden-Powell (2003), and Integrated environmental solutions (2015)

[a] Resistance R-value = thickness (m)/ Conductivity (W/mK)
[b] $U = 1/ (R_{SI} + R_{SO} + R_A + R_1 + R_2 + R_3 \ldots\ldots)$

Where R_{SI} = thermal resistance of internal surface

R_{SO} = thermal resistance of internal surface

R_A = thermal resistance of air spaces within construction

R_1, R_2, R_3, etc. = thermal resistance of successive components

Table A.4

U-value of roof

Layer/Surface	Thickness (m)	Conductivity (W/mK)	Resistance (m^2K/W)
Internal surface (ceiling)	-	-	.10
Ceiling tiles (polystyrene)	.0127	.032	.397 [a]
Ceiling boards	.00635	.14	.0454 [a]
Cavity (Loft space between flat ceiling and pitched roof lined with felt or building paper)	-	-	.18
Felt membrane	.002	.5	.004 [a]
Cavity (Gap between tiles and roofing felt or building paper)	-	-	.12
Slate tiles	.006	1.442	.004 [a]
External surface	-	-	.04
Total resistance			.8904 [a]
U-value			1.123 $m^2{\cdot}K/W$ [b]

Note. U-value calculation formula from Architects Pocket Book (Baden-Powell, Hetreed, and Ross, p154, 1997).

Lime plaster resistance figure from CLEAR (2015)

Thermal conductivity values sourced from Littlefield (2008), Baden-Powell (2003), and Integrated environmental solutions (2015)

[a] Resistance R-value = thickness (m)/ Conductivity (W/mK)
[b] $U = 1/ (R_{SI} + R_{SO} + R_A + R_1 + R_2 + R_3 ....)$

Where R_{SI} = thermal resistance of internal surface

R_{SO} = thermal resistance of internal surface

R_A = thermal resistance of air spaces within construction

R_1, R_2, R_3, etc. = thermal resistance of successive components

Table A.5

U-value of internal door

Layer/Surface	Thickness (m)	Conductivity (W/mK)	Resistance (m^2K/W)
Internal surface	-	-	.12
Wallpaper	.05	.14	.357 [a]
External surface	-	-	.12
Total resistance			.597
U-value			1.675 $m^2 \cdot K/W$ [b]

Note. U-value calculation formula from Architects Pocket Book (Baden-Powell, Hetreed, and Ross, p154, 1997).

Lime plaster resistance figure from CLEAR (2015)

Thermal conductivity values sourced from Littlefield (2008), Baden-Powell (2003), and Integrated environmental solutions (2015)

[a] Resistance R-value = thickness (m)/ Conductivity (W/mK)
[b] $U = 1/ (R_{SI} + R_{SO} + R_A + R_1 + R_2 + R_3 \ldots\ldots)$

Where R_{SI} = thermal resistance of internal surface

R_{SO} = thermal resistance of internal surface

R_A = thermal resistance of air spaces within construction

R_1, R_2, R_3, etc. = thermal resistance of successive components

Table A.6

U-Value for single glazed, timber frame window with normal exposure

Structure	Calculation	Area (m^2)
Frame (horizontal)	(1.524 x .05) x 2	0.1524
Frame (vertical) minus horizontal frame area	((1.2192-(.05+.05)) x .05) x2	0.11192
Mullion (vertical) minus horizontal frame area	((1.2192-(.05+.05)) x .05) x2	0.11192
Transom	(.5 x .05)	0.025
Total area of frame		0.40124
Total area of window		1.8580608
Percentage timber frame = (0.40124/ 1.8580608) x (100/1)		21.594557%
U-Value		4.7 $m^2 \cdot K/W$ [a]

Note. Overall window dimension = 5” (1.524m) x 4” (1.2192m)

[a] $U = 1/ (R_{SI} + R_{SO} + R_A + R_1 + R_2 + R_3 \ldots\ldots)$

Where R_{SI} = thermal resistance of internal surface

R_{SO} = thermal resistance of internal surface

R_A = thermal resistance of air spaces within construction

R_1, R_2, R_3, etc. = thermal resistance of successive components

Appendix B Heat loss rates calculated at 19oC, 20oC, and 22oC

Table B.1

Heat Loss Through Building Fabric at an Internal Temperature of 19^{o}C, with an External Temperature of 10^{o}C, the Mean Annual Temperature

Surface	Area m^2	Inside Temp ^{o}C	Outside Temp ^{o}C	ΔT ^{o}C	U-value	Loss in Watts
Roof	6.526 8	19	10	9	1.123	65.96 [a]
Floor	6.526 8	19	19	0	0.827	5.4 [a]
External wall (East)	8.63	19	10	9	1.7556	136.36 [a]
External wall (South)	4.56	19	10	9	1.7556	72.05 [a]
Internal wall 1	6.504	19	19	0	1.83486	11.9 [a]
Internal wall 2	2.568	19	19	0	1.83486	4.71 [a]
Internal wall 3	3.984	19	19	0	1.83486	7.31 [a]
Internal wall above door 4	.32	19	19	0	1.83486	.59 [a]
Window	1.858	19	10	9	4.7	78.59 [a]
Door	1.6	19	19	0	1.675	2.68 [a]
Total heat loss through fabric						385.55
Q_V = 1 x (5.67) x 9 x 0.33 = 16.84 watts lost through ventilation						16.84 [b]
Total Heat Loss through fabric and ventilation heat loss at 10^{o}C						402.39

Note. Standard equations from Metric Handbook Planning and Design Data (Littlefield 2008)

[a] Surface area m^2 X (inside ^{o}C – outside ^{o}C) X U-value of fabric = watts lost

[b] (Q_V) = V_a X volume X ΔT X ρC/3600

Where

Q_V = heat loss or gain in watts

V_a = ventilation rate in air changes per hour (ac/h)

ΔT = internal/external air temperature difference ^{o}C

ρC = volumetric heat capacity of air = 1200$Jm^{-3}K^{-1}$

Table B.2

Heat Loss Through Building Fabric at an Internal Temperature of 20°C, with an External Temperature of 10°C, the Mean Annual Temperature

Surface	Area m^2	Inside Temp °C	Outside Temp °C	ΔT °C	U-value	Loss in Watts
Roof	6.526 8	20	10	10	1.123	73.29 [a]
Floor	6.526 8	20	20	0	0.827	5.4 [a]
External wall (East)	8.63	20	10	10	1.7556	151.51 [a]
External wall (South)	4.56	20	10	10	1.7556	80.06 [a]
Internal wall 1	6.504	20	20	0	1.83486	11.9 [a]
Internal wall 2	2.568	20	20	0	1.83486	4.71 [a]
Internal wall 3	3.984	20	20	0	1.83486	7.31 [a]
Internal wall above door 4	.32	20	20	0	1.83486	.59 [a]
Window	1.858	20	10	10	4.7	87.33 [a]
Door	1.6	20	20	0	1.675	2.68 [a]
Total heat loss through fabric						424.78
Q_V = 1 x (5.67) x 10 x 0.33 = 18.71 watts lost through ventilation						18.71 [b]
Total Heat Loss through fabric and ventilation heat loss at 10°C						443.49

Note. Standard equations from Metric Handbook Planning and Design Data (Littlefield 2008)

[a] Surface area m^2 X (inside °C – outside °C) X U-value of fabric = watts lost

[b] (Q_V) = V_a X volume X ΔT X ρC/3600

Where

Q_V = heat loss or gain in watts

V_a = ventilation rate in air changes per hour (ac/h)

ΔT = internal/external air temperature difference °C

ρC = volumetric heat capacity of air = $1200 Jm^{-3}K^{-1}$

Table B.3

Heat Loss Through Building Fabric at an Internal Temperature of 22°C, with an External Temperature of 10°C, the Mean Annual Temperature

Surface	Area m^2	Inside Temp °C	Outside Temp °C	ΔT °C	U-value	Loss in Watts
Roof	6.5268	22	10	12	1.123	87.955 [a]
Floor	6.5268	22	22	0	0.827	5.4 [a]
External wall (East)	8.63	22	10	12	1.7556	176.12 [a]
External wall (South)	4.56	22	10	12	1.7556	96.07 [a]
Internal wall 1	6.504	22	22	0	1.83486	11.9 [a]
Internal wall 2	2.568	22	22	0	1.83486	4.71 [a]
Internal wall 3	3.984	22	22	0	1.83486	7.31 [a]
Internal wall above door 4	.32	22	22	0	1.83486	.59 [a]
Window	1.858	22	10	12	4.7	104.79 [a]
Door	1.6	22	22	0	1.675	2.68 [a]
Total heat loss through fabric						496.57
Q_V = 1 x (5.67) x 12 x 0.33 = 22.45 watts lost through ventilation						22.45 [b]
Total Heat Loss through fabric and ventilation heat loss at 10°C						519

Note. Standard equations from Metric Handbook Planning and Design Data (Littlefield 2008)

[a] Surface area m^2 X (inside °C – outside °C) X U-value of fabric = watts lost

[b] (Q_V) = V_a X volume X ΔT X ρC/3600

Where

Q_V = heat loss or gain in watts

V_a = ventilation rate in air changes per hour (ac/h)

ΔT = internal/external air temperature difference °C

ρC = volumetric heat capacity of air = $1200 Jm^{-3}K^{-1}$

Appendix C Technical data sheet for Rubitherm RT35HC

Data sheet

RUBITHERM

RT35HC

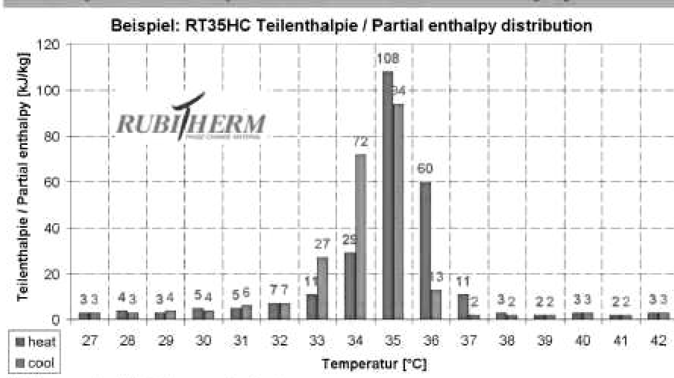
RUBITHERM® RT is a pure PCM, this heat storage material utilising the processes of phase change between solid and liquid (melting and congealing) to store and release large quantities of thermal energy at nearly constant temperature.
The RUBITHERM® phase change materials (PCM's) provide a very effective means for storing heat and cold, even when limited volumes and low differences in operating temperature are applicable.

We look forward to discussing your particular questions, needs and interests with you.

Properties:
- high thermal energy storage capacity
- heat storage and release take place at relatively constant temperatures
- no supercooling effect, chemically inert
- long life product, with stable performance through the phase change cycles
- melting temperature range between -4 °C and 100 °C

The most important data:

	Typical Values	
Melting area	**34-36** main peak: 35	**[°C]**
Congealing area	**36-34** main peak: 35	**[°C]**
Heat storage capacity ± 7,5%	**240**	**[kJ/kg]***
Combination of latent and sensible heat in a temperatur range of 27°C to 42°C.	**67**	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]**
Density solid at 25 °C	**0,88**	**[kg/l]**
Density liquid at 40 °C	**0,77**	**[kg/l]**
Heat conductivity (both phases)	**0,2**	**[W/(m·K)]**
Volume expansion	**12**	**[%]**
Flash point (PCM)	**177**	**[°C]**
Max. operation temperature	**70**	**[°C]**



*Measured with 3-layer-calorimeter.

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The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 22.01.2015

Figure C1 Rubitherm RT35HC technical data (Rubitherm, 2015)

Appendix D Technical data sheet for MickroCaps PCM slurry

MikroCaps
Encapsulate your Business

MikroCapsPCM35

An aqueous dispersion of microencapsulated paraffin wax.

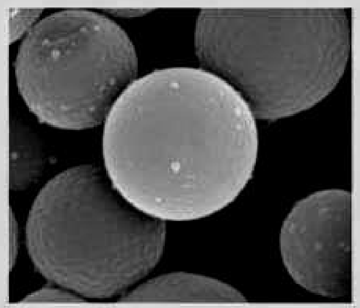
Composition

Classification: Phase Change Materials Microcapsule dispersion
Type of membrane: Melamine-formaldehyde
Type of PCM: Paraffin wax

Technical data

PCM content in the dispersion: 25-30%
PCM content in dry capsule: 80-85 %
Dry content in the dispersion: 35-38%
PCM melting area: 33-37 °C
Heat storage capacity (of dried microcapsules): 190-200 J/g

pH: 7,0-9,0
Density: 900-970 g/cm^3
Viscosity (at 25°C): 10-500 cPs
Appearance: White slurry
Average particles size: 1-20 µm



Storage and handling

Storage: Store at an even temperature between +5°C and 35°C.

Use: Capsule component may slightly precipitate, therefore please kindly stir it immediately before use using an overhead stirrer!

Shelf life: 6 months; A longer storage does not mean that the product is not usable anymore. The capsule component is likely to precipitate and coagulate however the capsule itself does not change in quality within one year if stored. If separation or precipitation occurs during storage, please kindly stir and check the specifications data.

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Figure D1 MikroCapsPCM35 technical data (MikroCaps, 2015)